NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

SYSTEMS ENGINEERING ANALYSIS CAPSTONE PROJECT REPORT

2024 UNMANNED UNDERSEA WARFARE CONCEPT

by

Team Alpha
Cohort 19

June 2013

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Potential adversaries throughout the world continue to acquire and develop sophisticated multi-layered, anti-access, area-denial (A2AD) systems. To maintain its maritime superiority, the United States must continue to innovate systems that are capable of operating in and defeating these A2AD environments. In particular, command of the undersea domain remains vital and will increasingly be critical in facing this future battle space.

The challenges our nation faces, however, are not limited only to the technological capabilities of the warfighters, but also include a myriad of confounding constraints. In addition to the expected shortfalls of mission-ready assets, the Submarine Forces also must address significant pressures in defense spending. Nevertheless, unmanned undersea vehicles (UUVs) remain one of the top priorities of the Chief of Naval Operations, as UUVs serve as effective force multipliers, while greatly reducing risk, in critical missions in A2AD environments.

This report presents the findings of analysis and assessment conducted by an integrated systems engineering and analysis team of military officer students at the Naval Postgraduate School. Their operationally driven tasking seeks to design a system-of-systems of unmanned and manned undersea vehicles to ensure undersea dominance both in the near term and into the next decade. The importance of the systems perspective to this study is reflected by the extensive engagement with many operational stakeholders, academic researchers, industry partners, and acquisitions programs across the Naval enterprise. The capability-based approach highlights the mission suitability of both currently fielded UUVs and also technologies realizable within the next decade. The capstone final report summarizes these critical insights and provides detailed recommendations to inform decision makers of the present to prepare for the undersea forces of the future.

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2024 UNMANNED UNDERSEA WARFARE CONCEPT

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ABSTRACT

Potential adversaries throughout the world continue to acquire and develop sophisticated multi-layered, anti-access, area-denial (A2AD) systems. To maintain its maritime superiority, the United States must continue to innovate systems that are capable of operating in and defeating these A2AD environments. In particular, command of the undersea domain remains vital and will increasingly be critical in facing this future battle space.

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LIST OF ACRONYMS AND ABBREVIATIONS

AoA	Analysis of Alternatives
ASBM	Anti-Ship Ballistic Missile
ASCM	Anti-Ship Cruise Missile
ASDS	Advanced Seal Delivery System
ASUW	Anti-Surface Warfare
ASW	Anti-Submarine Warfare
ATR	Autonomous Target Recognition
AUWS	Advanced Undersea Weapon System
AUV	Autonomous Undersea Vehicle
A2AD	Anti-Access Area Denial
CAIV	Cost as an Independent Variable
CN3	Communication Navigation Network Nodes
CNO	Chief of Naval Operations
COCOM	Combatant Commander
CONOPS	Concept of Operations
COTS	Commercial off the Shelf
CRUSER	Consortium for Robotics and Unmanned Systems Education and Research
CSG	Carrier Strike Group
DoD	Department of Defense
DoN	Department of Navy
DOTMLPF	Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, and Facilities
DRM	Design Reference Mission
DSRV	Deep Submergence Recovery Vehicle
DT&E	Developmental Testing and Evaluation
ESG	Expeditionary Strike Group
FFBD	Functional Flow Block Diagram
ISR	Intelligence, Surveillance, Reconnaissance

IO	Information Operations
LDUUV	Large Displacement Unmanned Undersea Vehicle
LCC	Life Cycle Cost
LCCE	Life Cycle Cost Estimate
LCS	Littoral Combat Ship
LMRS	Long-Term Mine Reconnaissance System
MCM	Mine Countermeasures
MILDEC	Military Deception
MOE	Measure of Effectiveness
MOP	Measure of Performance
NATO	North Atlantic Treaty Organization
NEC	Naval Enlisted Classification
NMS	National Military Strategy
NNPP	Naval Nuclear Propulsion Program
NSS	National Security Strategy
O&S	Operations and Support
ONR	Office of Naval Research
OSD	Office of the Secretary of Defense
RDT&E	Research, Development, Test and Evaluation
RF	Radio Frequency
RMMV	Remote Multi-Mission Vehicle
SEA	Systems Engineering Analysis
SIGINT	Signal Intelligence
SOF	Special Operations Force
SSBN	Nuclear Powered Ballistic Missile Submarine
SSGN	Nuclear Powered Guided Missile Submarine
SSN	Nuclear Powered Attack Submarine
TCS	Time Critical Strike
TDSI	Temasek Defense Systems Institute
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle

ULRM	Universal Launch and Recovery Module
UN	United Nations
USN	United States Navy
USV	Unmanned Surface Vehicle
USW	Undersea Warfare
UUV	Unmanned Undersea Vehicle
UUVRON	Unmanned Undersea Vehicle Squadron
VLS	Vertical Launch System

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EXECUTIVE SUMMARY

Ongoing research in the field of unmanned technologies led to the following 2013 Systems Engineering Analysis project tasking:

> **Design a system of Unmanned Undersea Vehicles (UUVs) that will provide an operational undersea force available for tasking over a range of missions by 2024. Consider current fleet structure and funded UUV programs as the baseline system of systems to conduct current missions. Include in your analyses attributes of the vehicles, payloads, projected costs, possible mission sets, and concepts of operations. The system may be a totally unmanned force or a combination force of manned platforms and unmanned undersea vehicles that can execute missions in an integrated fashion. A full range of alternatives should be considered. Of major importance in successfully deploying such a capability in the desired timeframe is acquisition strategy and DOTMLPF execution.**

In response to this tasking given by the Deputy Director for Warfare Integration and the Executive Director of Submarine Forces, **the SEA-19A project team recommends the following sustained UUV force structure**:

- 26 Large Displacement UUVs (LDUUVs)
- 120 Recoverable 21-inch UUVs
- 121 Expendable 21-inch UUVs

Total life-cycle cost for the proposed UUV fleet over its 20-year program is $3.65B (in FY13 dollars). This conservative estimate accounts for the entire life cycle, including procurement, continuous operations, maintenance, and training.

Four high-level decision drivers, based on the extensive concept generation modeling, simulation, analysis, lead to the above recommended UUV force structure:

1. **UUVs are essential to maintaining undersea dominance**. Increased operational capability and reduced risk for personnel and high value platforms are provided by unmanned systems. UUVs provide greater operational reach to both subsurface and surface manned combatants.
2. **Employment of multiple UUVs** provides a significant increase in successful mission accomplishment.

3. **Utilization of expendable UUV variants provides unique capabilities and cost savings**, especially for missions where probability of survival is low, or there is no need to recover the UUV.
4. An appropriate **balance of critical unmanned capabilities is required for effective** mission performance. All UUVs must have the capability to maneuver, survive, and persist in challenging environments. However, the cost vs. benefit analysis of advanced mission functionality often shows negligible gains in mission success, at a relatively disproportionate increase in cost.

Using a systems engineering methodology, SEA-19A addresses problems related to increasingly complex anti-access area denial (A2AD) environments. These environments require stealthy vehicles to execute critical mission sets. Stakeholder, functional, and mission-based analyses lead to the selection of the following four missions for inclusion in the proposed 2024 A2AD UUV concept of operations:

1. Intelligence, Surveillance, and Reconnaissance (ISR)
2. Information Operations (IO)
3. Mine Countermeasures (MCM)
4. Offensive Attack Operations (including ASW, ASUW, and offensive mining)

These operations are assessed to be the most likely missions that benefit in the near-term from UUV technologies by 2024. These assessments are based upon current programs of record and technology readiness levels across the Navy, and in industry and academia.

LDUUVs are a critical component of the proposed force structure due to the inherent capabilities of larger and more capable sensors, greater payloads, and longer endurance. Specifically, LDUUVs are required for persistent ISR and various offensive attack operations, but face operational and cost effectiveness constraints. Only 60-inch diameter and smaller LDUUVs are included in the analysis due to the operational constraints of the Universal Launch and Recovery Module in development for the Virginia Payload Module. To provide maximum operational flexibility, the Littoral Combat Ships are assessed to be feasible launch and recovery platforms for LDUUVs of this size.

Twenty-one inch and smaller diameter UUVs provide substantial capability for all proposed missions. The 21-inch UUVs are capable of being launched from all manned platforms, with the size only being constrained by current torpedo tube diameters. This effectively turns any manned platform into a UUV launch and recovery vessel. Analysis also shows that significant cost savings can be realized by designing several 21-inch variants as exclusively expendable.

Robust autonomous collision avoidance capabilities are key technology enablers which are necessary to reduce unanticipated UUV losses due to circumstances such as grounding and entanglement in fishing nets. Continued research needs to be conducted to develop innovative ways to overcome these operational issues. Until these technologies mature, the **employment of multiple UUVs in squads provides an advantageous solution** to maintain acceptable probabilities of mission success. This concept factors significantly into the proposed force structure.

To maintain the proposed sustained UUV force levels over the projected 20-year period, **a total of 35 LDUUVs, 167 21-inch Recoverable UUVs, 440 21-inch Expendable UUVs are to be procured**. The proposed acquisition strategy accounts for operational and training losses, while maintaining sufficient force levels for large-scale maritime battlespace preparation in an A2AD environment.

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The students of Systems Engineering Analysis Cohort 19, Team A would like to thank our advisor Dr. Timothy Chung, Assistant Professor of Systems Engineering, NPS, for his guidance and patience throughout the duration of our study.

SEA-19A would also like to thank the Systems Engineering Analysis curriculum faculty for their instruction and dedication to excellence in preparing us with the intellectual tools required to complete a study of this magnitude.

While many stakeholders provided excellent information and guidance, SEA-19A would specifically like to thank and acknowledge the following people for their contributions to our study:

RADM (ret.) Jerry Ellis, NPS

RDML (ret.) Rick Williams, NPS

CAPT (ret.) James Eagle, NPS

CAPT (ret.) Wayne Hughes, NPS

CAPT (ret.) Jeff Kline, NPS

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Organizations

Naval Surface Warfare Center, Panama City

Pennsylvania State University Applied Research Laboratory

Johns Hopkins University Applied Physics Laboratory

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I. INTRODUCTION

In 2002, former Chief of Naval Operations (CNO), Admiral (ret.) Vern Clark, introduced *Sea Power 21* which described the overarching vision of the U.S. Navy entering into the 21st century. In the document, he prescribed the use of unmanned vehicles for naval applications (Clark 2002). Admiral Clark understood the pivotal role that unmanned aerial vehicles (UAVs) played in modern warfare and saw the untapped potential of unmanned undersea vehicles (UUVs) to be critical force multipliers for naval operations.

With significant shortfalls in major naval platforms on the horizon, the Department of the Navy (DoN) continues to rely on technology to fill operational gaps and maintain highly favorable exchange ratios. In January 2012, the U.S. Director of Undersea Forces (OPNAV N97) published the *Unmanned Undersea Systems Strategy* which outlines the use of unmanned systems in future naval operations. Specifically, the document addresses the need to compensate for the future submarine shortfalls:

> **This Strategy provides a long-range vision, and a short-range way ahead, to develop a robust unmanned undersea vehicle capability for the Navy. This capability will improve coverage in environments challenging for manned platforms; provide responsive and far-forward coverage throughout all phases of conflict against traditional and emerging undersea threats; and extend the reach, and enhance the capability, of the attack submarine force to help compensate for the planned shortfall of SSNs and the retirement of SSGNs. (U.S. Director of Undersea Forces 2012)**

In September of 2012, SEA-19A was tasked by the Deputy Director for Warfare Integration (N9IB) Mr. Mike Novak and Executive Director of Submarine Forces Mr. Charles Werchado to study the evolving undersea force structure, focusing on a system-of-systems approach to manned and unmanned vehicle platforms, which will allow the United States to maintain undersea dominance both in the near term and into the next decade. The official tasking statement is as follows:

> **Design a system of UUVs that will provide an operational undersea force available for tasking over a range of missions by 2024. Consider current fleet structure and funded UUV programs as the baseline**

system of systems to conduct current missions. Include in your analyses attributes of the vehicles, payloads, projected costs, possible mission sets, and concepts of operations. The system may be a totally unmanned force or a combination force of manned platforms and unmanned undersea vehicles that can execute missions in an integrated fashion. A full range of alternatives should be considered. Of major importance in successfully deploying such a capability in the desired timeframe is acquisition strategy and DOTMLPF execution. Your research and analysis should consider and address these elements to the extent possible. (Novak and Werchado 2012)

A. PROJECT TEAM

The Systems Engineering and Analysis Cohort 19, Team Alpha (SEA-19A) Capstone Project Team consists of nine Naval Postgraduate School (NPS) students and several cross-campus subject matter experts. Six of the nine students are part of the Systems Engineering and Analysis (SEA) curriculum and the remaining three members are engineering students participating in the Singapore Temasek Defense Systems Institute (TDSI) program. The core project team and their respective backgrounds are shown in Table 1.

SEA-19A Capstone Project Advisor Dr. Timothy Chung (NPS Assistant Professor, Systems Engineering)
SEA-19A Technical Advisors RADM (ret.) Winford G. (Jerry) Ellis (NPS Chair of Undersea Warfare) RDML (ret.) Rick Williams (NPS Chair of Mine and Expeditionary Warfare)
SEA-19A Capstone SEA Students LT Mathiew Blandin (Surface Warfare Officer) LT Jeremy Brux (Surface Warfare Officer) LT Christopher Caraway (Surface Warfare Officer, Nuclear) LT Steven Hall (Surface Warfare Officer) LT J.P. Kish (Aviation, SH-60 Pilot) LT Stephen Szachta (Surface Warfare Officer)
SEA-19A TDSI Students LT Jamie Cook (Submarine Warfare Officer) LT Samuel Fromille (Submarine Warfare Officer) LT David Haertel (Submarine Warfare Officer)

Table 1. SEA-19A Project Team Composition

The team initially formed in September of 2012. At that time, only six SEA students were tasked with completing this study. Although several of the SEA students had previous operational experience as Anti-Submarine Warfare Officers and as prior enlisted submariners, it was important to add further undersea operational experience to the project team. In response to this need, three Submarine Warfare Officers were added in January of 2013.

Figure 1. SEA-19A Project Team Photo. From Left to Right, Top Row: Dr. Timothy Chung, LT David Haertel, LT Steven Hall, LT J.P. Kish, LT Mathiew Blandin; Bottom Row: LT Jamie Cook, LT Christopher Caraway, LT Samuel Fromille, LT Jeremy Brux, LT Stephen Szachta.

In order to build cohesive working relationships with warfighters, industry, and academia, our team has reached out to operational, naval enterprise and Naval Postgraduate School cross-campus stakeholders in order to provide a study that will heavily influence the future integration of unmanned undersea vehicles to the fleet. With the realization that unmanned technologies are revolutionizing modern warfare, we as

Naval Officers are responsible for fielding equipment that above all contributes to mission success.

B. PROJECT BACKGROUND

The United States Navy (USN) has a proud history of operation in the undersea domain. By continuously evolving and improving its warfighting strategies and technologies, the USN has established its commitment to dominance of the maritime environment. This project seeks to further that tradition of support by considering the current practice of Undersea Warfare (USW) with an appreciation for its impending inclusion of UUVs. The employment of unmanned systems in the undersea domain is a natural continuation of the well-recognized spirit of innovation in the USW domain.

Reflection on the history of USW provides perspective in understanding and assessing our current undersea capability, as well as insight into future challenges and advances that will be critical to continued success. Recognizing future implications is as critical as it is challenging. Remembering a 1904 British exercise in which five small Holland submarines tasked with harbor security sunk four warships, Admiral of the Royal Navy Jackie Fisher wrote, "It is astounding to me, perfectly astounding, how the very brightest among us fail to realize the vast impending revolution in Naval warfare and Naval strategy that the submarine will accomplish" (Commander Submarine Forces 2011). Recognizing the consequences of such miscalculations, the USN has committed to a rigorous consideration of the effects of undersea systems in naval operations.

Since World War I, militaries and other organizations have been exploiting the undersea domain for a variety of purposes: Intelligence, Surveillance, and Reconnaissance (ISR), covert insertion, coastal security, oceanography, kinetic combat operations, etc. Throughout World War II and especially the Cold War, advances in technology and accumulated operational experience drove the evolution of USW from maritime interdiction, through Anti-Submarine Warfare (ASW) and into the present mission environment of littoral ISR. The foundational military concept, which supports this USW construct, is the leverage derived from effective undersea concealment, otherwise known as stealth. The resulting operational impact is the ability to conduct undetected operations, to deliver effects without pre-alerting the adversary, to exploit

protective cover for greater survivability, and to operate inside an enemy defensive perimeter where other friendly forces cannot penetrate. (U.S. Director of Undersea Forces 2012)

Appreciation of a flexible USW concept is well documented in current U.S. Naval publications, including Undersea Warfighting and the Design for Undersea Warfare. These documents capture critical insights that motivate this project. The inherent capabilities and enabling attributes of undersea forces are basic tenets that must be embodied by a recommended solution system of unmanned assets.

> **Undersea forces, when used effectively, operate far forward and independently. They exploit stealth and survivability and carry offensive payloads. They penetrate adversary safe havens and hold critical assets at risk, whether those assets are ships, submarines, land targets or even critical information. (Commander Submarine Forces 2011)**

The development and employment of undersea systems is fundamentally complex and expensive. Systems uniquely capable of deterrence, intelligence collection, and ordnance delivery are further enhanced by leveraging the ability to penetrate adversary defenses, survive without significant defensive payloads, and exploit the ambiguity of the undersea domain. These complex missions place a high premium on technological innovation which is the substantial driver of program costs.

Operational ambiguity is a concept that can be abstract to those without first-hand experience. As a factor contributing to the effectiveness of undersea forces, it provides enhanced survivability and value of deterrence. Equally important is the challenge faced in design and operation of undersea systems in an environment where data always comes with qualifiers and the confidence of decisions must be weighed against carefully estimated risk.

> **In the air and surface domains, the un-aided human eye is capable of long-range detection of targets and, as a result, even unsophisticated adversaries can monitor those domains. Not only can targets be seen, but they can be quickly recognized and tracked with sufficient precision to enable making confident decisions. The contrast with the undersea environment could not be starker. (Commander Submarine Forces 2011)**

A leading priority is the ability to non-provocatively gain early access, far-forward in adversary safe havens. This addresses a primary need in the undersea force to challenge the impact of enemy Anti-access Area Denial (A2AD) systems. To ensure continued maritime superiority and effective global and regional deterrence, the undersea force will carry the mantle of assured access under hostile conditions. Specifically:

> **U.S. undersea forces must include a broad enough mix of platforms and systems such that there is no geographic location or depth of ocean-connected water that is beyond the reach of U.S. undersea forces. For maximum effectiveness, U.S. undersea forces will strive to deny potential adversaries any safe haven at all. (Commander Submarine Forces 2011)**

Current responsibility for assured access rests primarily with the submarine force, which can be limited by platform size and water depth. Additional constrains are projected force size reductions in the SSN fleet and the impending retirement of SSGNs. To meet those challenges and further enhance capabilities, this project will examine the role of unmanned undersea systems. This opportunity to maintain mission coverage and increase operational reach is documented throughout the guiding literature for the U.S. undersea force. A robust unmanned undersea vehicle capability for the Navy will:

> **Improve coverage in environments challenging for manned platforms; provide responsive and far-forward coverage throughout all phases of conflict against traditional and emerging undersea threats; and extend the reach, and enhance the capability, of the attack submarine force to help compensate for the planned shortfall of SSNs and the retirement of SSGNs. (U.S. Director of Undersea Forces 2012)**

The international strategic environment amplifies the significance of this objective. The eight assumptions delineated in the original publication of the *Design for Undersea Warfare* are:

- A chaotic and disorderly global security environment will increase demands on the U.S. Navy and U.S. Undersea Forces.
- Globally proliferating submarines are increasing pressure on freedom of the seas and contesting our undersea superiority.
- A2AD systems challenge our surface and air forces, placing increased responsibility on our undersea forces to enable Assured Access for the Joint Force.

- America's vital undersea infrastructure (energy and information) is becoming even more critical and more vulnerable.
- Our shrinking submarine force size requires that each platform must individually support more requirements across a broader area.
- Deterrence provided by our stealthy, agile, persistent and lethal submarines (SSBNs, SSNs and SSGNs) will remain important against both state and non-state actors.
- Ubiquitous media presence means we will need to exploit our concealment to provide our leadership options by remaining undetected and non-provocative when desired.
- The expanded decision space that undersea forces provide will be increasingly valued by senior leadership as the security environment grows in complexity, leading to increased requests for undersea support.

These assumptions outline a setting in which global proliferation of submarines, advances in A2AD systems, and ubiquitous media coverage will stress the USN ability to conduct operations in support of national objectives. This environment will be further exacerbated by force size reductions, expanding criticality of friendly undersea infrastructure, and increasing demand for undersea missions.

The project team seeks to address the problem of effectively integrating unmanned undersea systems into the existing force in support of current and future USW initiatives.

C. LITERATURE REVIEW

Beyond the source documents and literature aforementioned, this study incorporated and researched many other publications to provide a firm academic foundation to build upon. The literature review began with a broad foundational basis of the need for undersea dominance in the current environment. Technical documentation such as individual mission areas, detailed unmanned systems development and previous research related to our topic were then analyzed to determine what is feasible within our given timeframe. The goal of this project is to develop the future force structure of undersea forces focusing on the inclusion of UUVs. This force structure will be a combination of manned and unmanned systems to ensure undersea dominance and unfettered access to the global maritime environment. To this end we synthesize and analyze research that has been previously conducted. This research provides a critical

understanding and background for the application of the systems engineering process and in depth qualitative and quantitative analysis.

The overarching strategy document addressing the security needs and goals of the United States of America is the *National Security Strategy* (NSS) of May 2010, which is approved by the President of the United States. This document outlines the current world strategic geopolitical situation as well as security goals and needs of the United States. The Department of Defense (DoD) is just one of many elements that are required to execute the NSS. There are very clear statements on the responsibility of the DoD, which accounts for seventy percent of all federal procurement spending, to be responsible stewards of taxpayer funds. This responsibility necessitates that the weapon systems procured should offer exceptional capabilities to warfighters while providing an exceptional value to the taxpayer.

To address the military contribution to the security of the United States of America, the 2011 *National Military Strategy* (NMS) "emphasizes how the Joint Force will redefine America's military leadership to adapt to a challenging new era." This document acknowledges the ever-changing environment and delineates that the military will ensure access to and freedom of maneuver within the global commons. Future capabilities will include "modular, adaptive, general purpose forces that can be employed in the full range of military operations." A unique aspect of this document is that it addresses the demanding and dangerous A2AD environment. It states that Joint Forces will train and exercise in degraded air, sea, cyber, and space environments. It acknowledges and respects the ability of sophisticated adversaries to deny the United States the traditional advantage of technological superiority. The NMS gives broad direction for the force structure of the future maritime force.

> **Joint forces will include an appropriate mix of small, mission tailored and large, multi-mission capable units, formations and platforms. This will provide the ability to conduct the full range of naval operations across the spectrum of maritime environments. (Chairman of the Joint Chiefs of Staff 2011)**

The NSS and NMS lay the broad framework for how the U.S. military executes strategy to ensure the security of the nation. The 2007 *Cooperative Strategy for 21st*

Century Seapower details the overarching strategic goals of the sea services. The sea service goals of ensuring access to the global commons and preserving the oceans as a source of security and prosperity are expounded upon and specific details regarding how security and stability are achievable are detailed. The main principle of the strategy is a combat force that is credible and capable of winning wars while at the same time deterring aggression. A key point of the document is that "preventing wars is as important as winning wars." This is done through cooperation with allies as well as "regionally concentrated, credible combat power" that is "globally distributed as mission tailored maritime forces."

From the Maritime Strategy of the United States and the ultimate source document, the United States Constitution, the mission of the United States Navy is established. "The mission of the Navy is to maintain, train and equip combat-ready naval forces capable of winning wars, deterring aggression and maintaining freedom of the seas." This constitutionally authorized requirement on behalf of the American citizenry is the ultimate foundation for this study, our daily operations, and the missions and visions of the warfare communities that comprise the USN.

The submarine force has a firm vision linked directly to all of the aforementioned documents. The vision of the United States Submarine Force is:

> **The U.S. Submarine Force will remain the world's preeminent submarine force. We will aggressively incorporate new and innovative technologies to maintain dominance throughout the maritime battlespace. We will promote the multiple capabilities of submarines and develop tactics to support national objectives through battlespace preparation, sea control, supporting the land battle and strategic deterrence. We will fill the role of the Joint Commanders' stealthy, full spectrum expeditionary platform. (Submarine Warfare Division [N77] 2013)**

Possessing key capabilities such as stealth and combat power, the submarine force is able to address many of the issues and requirements delineated in our master strategy documents. The development of UUVs and integration into the current undersea force has a direct link to the vision of the submarine force as well as the other supporting documents.

Specific documents that detail the development of UUVs are the *Design for Undersea Warfare*, the *UUV Master Plan*, the USN *UUV Roadmap*, and the *Unmanned Undersea Systems Strategy*. These documents give a detailed outline of the mission sets that are applicable or potentially applicable to UUVs and a broad outline of the introduction of UUVs in to the fleet. The USN UUV Roadmap is especially useful as it provides an initial framework with which to examine mission sets.

From broad strategy documents the project team progressed towards more specification and detail oriented documentation. To gain a deep understanding of the technical issues involved with the development and employment of UUVs the project team attended a week long short course at Pennsylvania State University's Applied Research Laboratory (Penn State ARL). The topics covered in this course ranged from broad missions to detailed specifications of existing vehicles and vehicles in development. Propulsion, sensors, navigation, communications, control systems, and communications were covered in great detail. Nearly all technical aspects of UUVs were addressed, giving the team an excellent foundation grounded in technical reality. Following the Penn State ARL short course the team examined previous Naval Postgraduate School (NPS) Systems Engineering thesis projects that related to UUVs.

The first thesis that was researched was the Systems Engineering and Analysis Cohort 17, Team Alpha (SEA-17A) June 2011 thesis titled "Advanced Undersea Warfare Systems." This thesis developed the Advanced Undersea Weapons System (AUWS) concept. This concept is a long term vision of a family of theoretical vehicles that operate in both sea surveillance and attack modes. It is a novel concept that opens the door to a more offensive use of unmanned vehicles in the undersea domain. The key differentiation between the AUWS concept and the SEA-19A proposal is that the AUWS system only addresses systems used for offensive attack and mining. The SEA-19A report is designed to provide a future force structure of various vehicles, over a range of applicable missions.

Another 2011 thesis that was researched was "A System to Integrate UUVs with a Submarine Host Platform" (Calvert et al. 2011). This systems engineering thesis lays out specific integration issues and provides recommendations for the operation of UUVs

from SSNs. Many of the issues discussed are addressed in the development of the submarine universal launch and recovery module (ULRM) that is currently in development. The SEA-19A project goals are broader than those of the Calvert thesis and address the implementation of a system-of-systems involving multiple UUV platforms.

Other NPS theses were examined and a recurring theme was that the theses addressed specific vehicles and associated capabilities or were very broad and forward looking. The SEA-19A project, in contrast, is directed at the near-term and addresses UUVs and undersea dominance from a system-of-systems perspective.

D. SYSTEMS ENGINEERING PROCESS AND PROCESS MODEL

The systems engineering process is iterative in that it continuously revisits project sections in an effort to continually improve solution recommendations. Considerable effort is given to avoiding convergence to a solution too early in the study process. To guide the project team and allow traceability through this process, a process model was tailored to this project's needs. Due to the fact that this project will not go through prototype development and production with subsequent implementation into test and operations phases, the project team determined that a waterfall systems engineering process model best fits this project.

A generic waterfall process model (Figure 2) is modified due to the complexity of the problem and to focus on the processes leading up to system design. With multiple mission sets being considered for the future force structure, the project had to take a system-of-systems approach. Knowing that a system-of-systems approach was necessary and knowing that multiple missions needed to be performed by the force, the problem was initially worked using a bottom-up approach. This meant functional decomposition had to be done on each mission separately, which would in turn provide insight into how the system would function as a whole. The final tailored waterfall diagram developed for the project is represented in Figure 3.

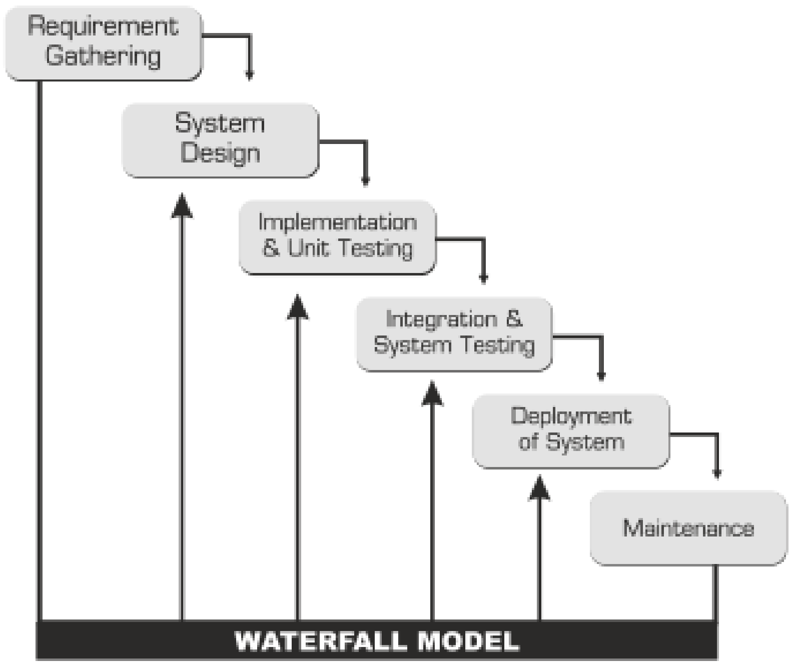

Figure 2. General Systems Engineering Waterfall Model (From SQTLAB, 2012). General waterfall model used to sequentially step through phases of system development beginning with initial conceptualization and concluding with the operations and support of deployed systems.

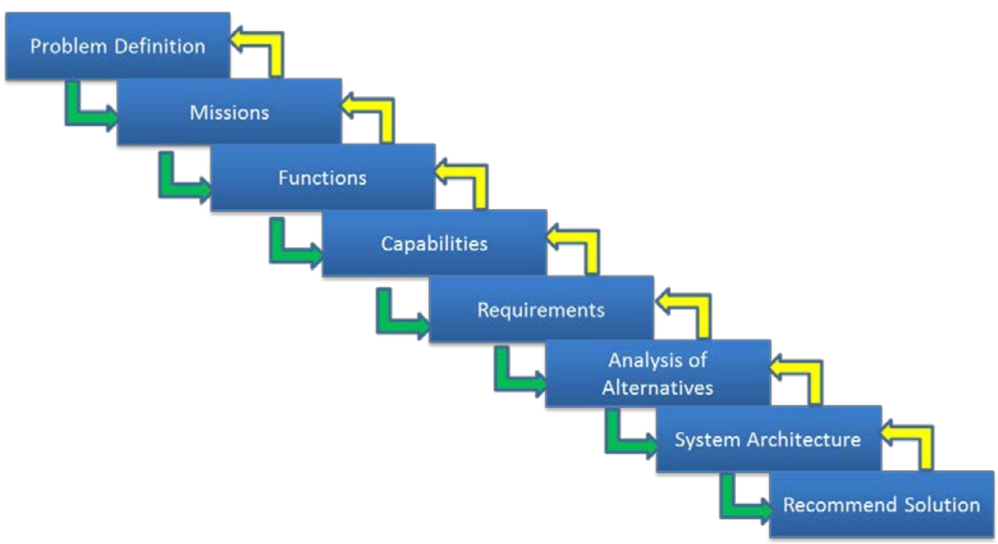

Figure 3. Tailored Waterfall Model Process Diagram. The SEA-19A tailored waterfall model uses a mission based approach to analyze system functionality, capabilities, and requirements. This information is used to determine notional system architectures and recommended force structures. Green arrows below the boxes indicate sequential processes and the yellow arrows above the boxes indicate iterative feedback loops used to revisit previously completed processes.

As seen in Figure 3, much of the generic process is still intact. With any system engineering process the first thing developed is the problem definition. In the problem definition stage stakeholder analysis, needs analysis, initial scoping and technical research are performed. From these activities, the need to look at each mission set separately is determined. During the mission analysis process, mission specific functional decomposition/flow analysis, design reference mission (DRM) development and re-scoping are performed. The mission functional decompositions are then consolidated to determine how the overall system needs to function which led to the development of the concept of operations. This provides the direction needed to determine the system capabilities required in order to not only perform the missions but to also have a desired level of sustainment. After capabilities are determined more research is conducted to determine a list of requirements for the UUV force, which are feasible with consideration to existing and emerging technology.

After developing requirements, an analysis of alternatives is performed to see if the missions to be performed would benefit from using UUVs. In the analysis of alternatives existing platforms are examined and compared to the notional UUV force with consideration to cost vs. capability to determine whether UUVs are needed. Once the usefulness of UUVs is validated, system architecture is developed with an emphasis on Doctrine, Organization, Training, Material, Leadership and Education, Personnel, and Facilities (DOTMLPF). From the notional system architecture a recommend solution is presented.

E. ORGANIZATION OF REPORT

The basic outline of this project report roughly follows the same logical flow seen in our tailored systems engineering process model (Figure 3). A thorough background research (Chapter I) and stakeholder analysis (Chapter II) are completed to determine current UUV capabilities and fleet needs with respect to undersea dominance.

Functional understanding (Chapter IV) of the systems under review is a critical component of all systems engineering efforts. This allows development of system requirements while at the same time, attempting to remain solution neutral. With a firm grasp on underlying system operation and functionality, our project then had to be scoped

(Chapter III) to reasonable expectations. This allowed the team to focus efforts on mission sets dedicated to providing new and improved capabilities in the context of an A2AD environment (Chapter V). With mission sets determined, specific requirements and capabilities are then identified.

Modeling and simulation (Chapter VI) is used to explore different system attributes and configurations within a simulated A2AD environment. The analysis of alternatives (Chapter VII) takes all of the quantitative data obtained from modeling and simulation, and combines it with qualitative data to provide decision makers with system alternative rankings and assessments.

One of the more difficult tasks is determining how much developmental systems are going to cost taxpayers (Chapter VIII). With very few historical UUV systems to draw data from, other systems such as torpedoes had to be used to develop cost estimation models.

The final deliverable of this report is the recommended force structure (Chapter IX). Great effort is placed on recommending a total system that can meet the objectives of the proposed CONOPS. A time-phased acquisition and implementation plan, along with a conservative program cost estimate are included to provide realistic program readiness expectations and to identify required funding and technology enablers to make the program a reality.

Finally, several key concepts and innovative ideas discovered throughout the systems engineering project are presented to provide context for future studies and research (Chapter X). This also includes areas of analysis that are included as part of this study, but can benefit greatly from additional, focused research.

F. REPORT CONTRIBUTIONS

Potential adversaries throughout the world continue to acquire and develop sophisticated multi-layered, anti-access, area-denial (A2AD) systems. To maintain its maritime superiority and undersea dominance, the United States must continue to innovate systems that are capable of operating in and defeating these A2AD environments.

Unmanned Undersea Vehicle (UUV) research and development remains one of the CNO top priorities. UUVs may serve as effective force multipliers, while also providing significant extensions of capability to current and future manned platforms.

SEA-19A's mission is to provide unbiased, cutting-edge research and assessment in the domain of unmanned undersea warfare. As Naval operators ourselves, our goal is to make recommendations that provide warfighters with the tools necessary to execute undersea missions, when and wherever directed. Significant modeling and simulation efforts have been undertaken to analyze the mission effectiveness of UUVs operating under the purview of the derived *2024 UUV Concept of Operations*. Analysis of the resultant data has been used to develop a notional, build-to force structure that consists of two classes of UUVs: Large Displacement UUVs (LDUUVs) equipped for ISR and offensive attack operations, and 21" and smaller UUV variants capable of operations within all mission areas. Another concept vehicle analyzed is a new UUV glider mine variant for offensive area-denial operations.

Innovative UUV concepts derived over the course of study include: Covert Q-route mapping operations for high value unit passage through mined areas, long-endurance decoy and deception operations, mobile minefield networks, and UUVs designed for expendability.

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II. NEEDS ANALYSIS

A. STAKEHOLDER ANALYSIS

Stakeholders are defined as any entity, internal or external, which can directly or indirectly affect the problem or be affected by the problem or recommended solutions (Romeo 2008). Stakeholder analyses are used to identify, classify, assess, and determine the individual needs and wants of stakeholders. The two critical components generated from this stakeholder analysis are first an accurate and well-defined problem statement, and second a detailed list of system needs (Table 3) that is used to generate system requirements.

The goal of the systems engineering process as a whole is to pair the right solution with the right problem. Understanding the right problem requires an in-depth analysis of both the supply and demand aspects of a given problem. Systems delivered to the fleet are all too often either over budget, behind schedule or do not meet the needs of the users (Defense Acquisition University 2001). Likewise, users often want more from a system than a manufacturer is able to provide due to technological or financial constraints. Thorough stakeholder analysis seeks to link the needs of all stakeholders into one coherent document that can, in turn, be used to identify and define specific system requirements.

Identification and Classification

In order to obtain exposure to the community of UUV development and operations, the SEA-19A project team met on-campus with several influential leaders of innovation, industry, and the operation of UUVs. Initial stakeholder interactions included: SEA-19A project sponsor Mr. Mike Novak (OPNAV N9IB), Mr. Charles Werchado (Executive Director of Submarine Forces), Captain Jeffery Jablon (Commander Submarine Development Squadron [SUBDEVRON 5]), Mr. Bill Glenney (Deputy Director CNO Strategic Studies Group), Mr. John Benedict (Johns Hopkins Applied Physics Laboratory [Johns Hopkins APL] / LDUUV AoA Director), Dr. Timothy Chung (SEA-19A Thesis Advisor / Consortium for Robotics and Unmanned

Systems Education and Research [CRUSER] Director of Research and Education), and several other NPS subject matter experts (SMEs).

In order to further broaden our foundation of unmanned technologies and capabilities, select members of the SEA-19A project team attended several naval enterprise meetings and site visits as shown in Figure 4, notably including: Penn State ARL Undersea Technology Short Course, Office of Naval Research (ONR) Unmanned Systems Review in Panama City, CRUSER Warfare Innovation Workshops at NPS, Boeing in Seattle, the Columbia Group in Panama City, General Atomics in San Diego, and Liquid Robotics in Sunnyvale.

Figure 4. U.S. Naval Enterprise Stakeholders. The majority of SEA-19A stakeholder interactions took place with Naval Enterprise organizations. Significant interactions include: Penn State ARL, Johns Hopkins APL, NAVSEA Panama City, Office of Naval Research, The Columbia Group, and DEVRON Five.

The project team also interacted with battle force commanders in order to elicit their operational perspectives on issues they currently face and are expecting in the future with respect to capability gaps and how UUVs could be utilized as force multipliers. We reached out to the following operational military stakeholders as shown in Figure 5: Commander Submarine Forces, Commander Submarine Forces Pacific, Submarine

Group 7, 8, and 10, Task Force 54, 69, and 74, as well as various Mine Countermeasure (MCM) and Surface Commander Task Forces.

Figure 5. U.S. Military Operational Stakeholders. Operational stakeholder analysis is conducted primarily through documentation and instructions available from the various Submarine Commanders around the globe.

These meetings and site visits enabled the project team to meet and interact with a variety of operational, naval enterprise, and academia stakeholders. Since the focus of our study is on a system-of-systems approach, stakeholders are classified and grouped into broad categories rather than mapping each individual stakeholder to each need (Langford 2007). This approach leads to reduced bias towards individualized opinions or recommendations presented by stakeholders, during background research.

Identified stakeholders are classified into the following the groups:

1.0 Investors

2.0 Developers

- Conceptualizers
- Designers
- Builders

3.0 Infrastructure providers

4.0 Infrastructure supporters

5.0 Operators

6.0 Customers

7.0 Partners

8.0 Suppliers and supply chain partnerships

9.0 Competitors

10.0 Adversaries

Stakeholders are classified in this manner to encourage the project team to analyze UUV systems from multiple perspectives. This also prevents the project team from being heavily influenced by stakeholders attempting to market privatized products for corporate gains.

Primitive Needs

Once stakeholder classification is completed, the next step is to identify and understand the primitive needs and wants of each class in order to further define the problem and form the foundation for effective needs. Primitive needs are the most basic needs of stakeholders. For example, a civilian manufacturer needs to make a profit and the customer needs the system to operate as designed and complete desired mission objectives. Table 2 shows each classification group, with a working definition of that group, associated entities, and their root primitive needs.

Table 2. Stakeholder Primitive Needs. To generate the systems primitive needs, general stakeholder classifications are generated, defined, and analyzed for respective needs.

Stakeholder CLASSIFICATION		**Definition**	**ENTITIES**	**PrimItive Need**
1.0 Investor		Those who give authority over assets or resources in exchange for a return on investment.	U. S. Government, CNO, OPNAV, NAVSEA-SYSCOMS, PMO/PMA	To obtain a significant operational return on UUV investment and fulfill operator and customer's needs in order to maintain undersea dominance.
2.0 Developers	Conceptualizers	Those who imagine and idea for generation and evaluation from data or experiences.	NPS, ONR, academia, nonprofit research groups, commercial defense companies	To create or advance UUV concepts that will be developed into operational systems to fill an emergent need.
	Designers	Those who creates and often executes plans for a project or structure.	Program managers, commercial defense companies	To design UUV systems that meet operational requirements.
	Builders	Those who build or supervise building according to a systematic or process.	Commercial defense companies	To build UUV systems in return for compensation.
3.0 Infrastructure Providers		Those who build or construct the basic framework or underlying foundation of the system.	TRANSCOM, Port Authority, NAVFAC, host vessels, defense facility contractors	To provide an operational UUV system infrastructure that supports the system life cycle and designed intent.

Stakeholder CLASSIFICATION	Definition	ENTITIES	PrimItive Need
4.0 Infrastructure Supporters	Those who maintain and operate the basic framework or underlying foundation of the system.	Maintenance crews, public works companies, TRANSCOM, NAVFAC, host platforms, defense facility contractors	To ensure continued operation and maintenance of UUV system infrastructures throughout the system life cycle.
5.0 Operators	Those who physically operate and maintain the system.	USN Sailors, government contractors, maintenance personnel	To utilize and maintain UUV systems to achieve mission objectives.
6.0 Customers	Those who acquire systems for use in operational environments.	COCOMs, intelligence agencies, civilian support companies	To man, train and equip operators with highly capable UUV systems to maintain undersea dominance.
7.0 Partners	Those who share in the system results but operate independently from the system.	Coalition forces, UN, other military entities	To share the benefits from the completion of UUV mission objectives.
8.0 Suppliers	Those who provide for the system to include products or services.	Commercial retailers, industrial manufacturers, hardware/software producers, parts suppliers, training centers	To provide customers and operators with the materials and services needed to operate and maintain UUV systems.

Stakeholder CLASSIFICATION	Definition	ENTITIES	PrimItive Need
9.0 Competitors	Those who are rivals in the production, support, or operation of the system.	Commercial defense contractors.	To have market competition that drives technological innovation and cost effectiveness of UUV systems.
10.0 Adversaries	Those who contend with, oppose, or resist the intent of the system	Opposing forces, activists	To resist or defeat the intent of deployed UUV systems.

Effective Needs

Determining the stakeholder effective needs is necessary to generate the overall system needs that in turn are used to generate system requirements. This process is often referred to as the stakeholder requirements definition process which is intended to elicit, negotiate, document, and maintain stakeholders' requirements for the system of interest within a defined environment. This part of the stakeholder analysis focuses on the specific needs of stakeholders that are of critical importance to system design and operation.

The effective needs of each stakeholder classification have been discovered through background research and through direct interactions with individual stakeholders. The following sections, which are broken down by stakeholder classification, document the stakeholder effective needs and supporting documentation.

1.0 Investors

The investor group effective need is to maintain undersea dominance of the seas as related by direct statements from those in the key roles in the United States Government.

> **Undersea dominance is critical to the security of the nation. It is a warfare area assigned, uniquely, to the Navy alone….This is the one domain in which the United States has clear maritime superiority – but this superiority will not go unchallenged. (Chief of Naval Operations 2011)**

Related to this primary need, investors also stressed the importance of the need "to have the ability to defeat complex A2AD environments" (Chief of Naval Operations 2012).

The CNO has also expressed the need to press forward with the implementation of UUVs into the fleet. Unlike the military services' relatively fast acceptance of several UAV platforms, the Navy has been slower to progress and integrate UUV platforms into the fleet due to significant communication and command/control issues (Whitman 2002). In an effort to place focus on UUV development and integration, the CNO has set a goal of obtaining a "squadron of ten operational large diameter unmanned undersea vehicles

(LDUUVs) by 2020 and to increase the endurance for a LDUUV to be able to conduct fully independent 60 day missions by 2017” (Chief of Naval Operations 2011).

The investors’ needs also require that UUV development and integration be executed in a cost effective manner. President Barack Obama directly said in regards to maintaining freedom of the seas that we must “spend the taxpayers’ dollars wisely” (White House 2010). Especially with looming budget cuts projected in the near future, the need to ensure that systems engineering processes are followed can even be traced to our teams’ assignment to this project. Cost is one of the driving factors of any project and the goal of any systems engineering process is to design systems that meet the triple constraint of cost, schedule and performance (Defense Acquisition University 2001). Several investors have also expressed the need to leverage proven technologies and investments that have already been made in an effort to bring immediate UUV capabilities to the fleet, which can fill critical capability gaps. Finally, several investors stressed the importance of the need for affordable force multipliers in the undersea domain to augment the submarine fleet.

2.0 Developers

Simple economics drive the primary need of developers. Stakeholders in this classification need to make a profit, stay in business, or obtain specific returns from the system. To ensure adequate and ongoing compensation, organizations and businesses need to advance emerging technologies, build quality products, and meet the needs of customers in a cost effective manner.

A stated UUV system developers’ need is to incorporate modular system designs. This allows UUVs to share common hardware/software such as propulsion units, sonars, obstacle avoidance programs, and hulls. “Unmanned vehicle systems must employ modular hardware and software design, and an open system architecture that will support rapid, affordable insertion of new technologies and payloads” (Piggott 2006). Modularity is also closely tied with the need for UUV systems to utilize commercial off the shelf (COTS) products. This is not only important at component levels, but there are also several proven, commercially available UUVs and UUV products, such as software, that can be directly used for military applications. “As systems continue to increase in size

and complexity, researchers continue to investigate improvements in engineering methodologies in order to build systems of high quality, in reduced time, and cost effectively. The use of COTS components is viewed as a solution to these problems" (Tumuluri 2001).

The developer group also has a need to create systems that can operate and survive in harsh maritime environments. Compared to both UAVs and USVs, significant complications such as platform endurance, seawater intrusion, undersea communications, and limited visibility make many UUV missions extremely difficult to execute. "Corrosion, bio-fouling, extreme pressure, and unpredictable marine environments place demands on UUVs that have no analogy on land or in air" (Frink 2012).

3.0 Infrastructure Providers / 4.0 Infrastructure Supporters

To be considered effective in an A2AD environment, UUV systems need to possess a high degree of operational availability. A significant portion of operational availability is the ability for the system to be mobile and easily transportable to mission areas around the world. UUV platforms are inherently slow and have limited endurance when compared to other undersea and surface maritime combat units. These factors drive the need for UUV systems to be integrated into other stealthy units such as submarines, LCSs, and aircraft to reduce transit distances to operational areas. Constraints, such as size and weight limitations related to ULRMs, torpedo tubes, LCS cranes, and aircraft payload bays, are all important considerations when generating UUV support requirements.

5.0 Operators

The primary need of all operators is that systems successfully accomplish the missions for which they are designed. Operators also need systems that exhibit a high degree of the "ilities" such as reliability, maintainability, and availability.

Due to habitability constraints of many host vessels, operators need to be equipped with systems that are relatively easy to operate and maintain. LCS and submarine platforms have been designed with minimal manning in mind and UUV systems need to minimize manpower footprints aboard these vessels (Government

Accountability Office 2007). In keeping with efforts to re-engage USN sailors as the primary operators of naval systems, UUV systems should use USN sailors rather than civilian contractors to perform organizational level maintenance and operations to the greatest extent possible. Systems that are easy to operate are anticipated to reduce the cost in training new operators, decrease operator error, and increase overall operational safety. Ideally the systems will have extremely high reliability and low maintenance requirements so that systems can be integrated without effecting the current naval manning requirements of host vessels.

UUV systems need to be safely transported, deployed, operated, recovered, and maintained. Many UUVs utilize high-power density battery systems that may be potentially volatile or otherwise dangerous. Among other complications, this issue was one of the primary reasons for the setbacks to the Advanced Seal Delivery System (ASDS) program in 2008 (Cavas 2008). As such, advanced fault mitigation systems and procedures need to be implemented to reduce the risk of fire or explosion onboard host platforms.

Specifically in regards to submarine operations, launch and recovery of UUV systems cannot reveal the position of the submarine. UUV systems are intended to be affordable force multipliers that extend the reach and coverage of manned platforms. They are not intended to place our high value assets at risk. Either technological improvements to reduce noise generation or evolved operational procedures need to be implemented to limit the acoustic exposure related to submarine UUV operations.

6.0 Customers

The primary need of the customer is to provide operators with the assets, training, and support necessary to execute mission directives. This need includes the identification of capability shortfalls and needs that can effectively be executed by UUV platforms in support of undersea dominance.

Customers essentially act as the “middle men” between operators and both investors and developers. The primary objective of the customer is to fight and win America’s wars. To achieve this objective, customers need to effectively balance the cost, schedule, and performance factors of UUV system acquisition. Often in warfare, a

limited capability is better than no capability at all. To this end, nearly all customers have expressed the need to bring UUV capabilities immediately to the fleet. This led to the need for our systems engineering process to develop a time phased approach to UUV implementation.

Significant financial constraints will continue to influence military decisions over the next decade. Customers need to demand that UUV systems are built with a high degree of modularity so that as technologies mature, they can be inserted into existing UUV system structures. Modularity also needs to be stressed so that UUV platforms can be utilized to perform multiple mission sets, thereby reducing total system ownership costs.

Due to the assumed A2AD operational environment, UUV systems also need to incorporate a certain degree of operational expendability. The cost of losing or scuttling a UUV needs to be much lower than the cost of losing major platforms. Several stakeholders have even expressed the need for some UUVs to be designed as purely low cost, expendable platforms.

7.0 Partners

There are very few nations currently pursuing unmanned undersea technologies for military applications, but trends are suggesting that the total numbers of UUV systems worldwide will double over the next decade (Defense Security Service 2011). Although many of our coalition partners do not have a significant monetary stake in the development of UUV systems, they may directly benefit from the increased undersea capabilities afforded by these systems.

Partners may need to know the UUV capabilities available to a COCOM. An increasingly joint and multi-national operational environment necessitates that all members of the coalition be at least aware of the general capabilities of military assets. For the sake of advancing UUV technology and effectiveness, partners with similar objectives need to jointly cooperate and share in the responsibility of UUV development and implementation.

8.0 Suppliers / 9.0 Competitors

Suppliers need to have adequate UUV repair parts and consumables in stock to maintain high levels of operational availability. Effective systems of systems also need to exhibit a fair amount of market competition. This leads to higher quality products at relatively lower costs to the customer (Kranton 2001). This need also encourages developers to advance developmental technologies using internal research and development funds in order to outperform the competition and secure contracts with suppliers and customers.

10.0 Adversaries

Military adversaries need UUV systems to not perform as designed and not meet mission objectives. A2AD environments are carefully designed to counter the military efforts of opposing forces. As UUV systems continue to increase in both capability and in quantity, adversaries need to look for ways to counter these threats. Likewise, the United States and its allies need to anticipate future UUV proliferation and develop defensive strategies and counter-UUV systems. Figure 6 shows many of the countries around the world (including allies, neutrals, and potential adversaries) who are currently pursuing UUV technologies.

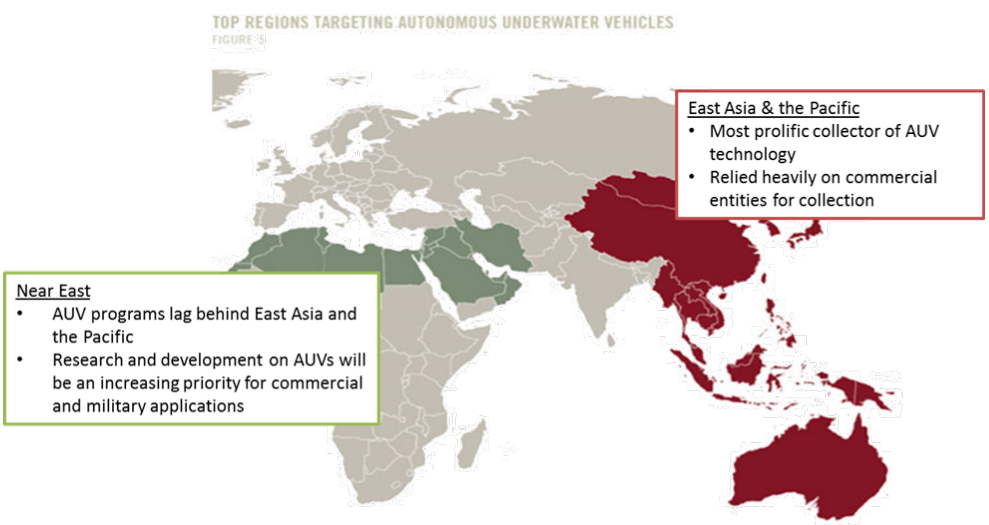

Figure 6. Top Regions Targeting UUV Development (From Defense Security Service 2011). Several countries around the world are actively pursuing UUV technology for both military and commercial applications. UUV development in East Asia exceeds that of any other area in the world.

Potential adversaries also include those internal to the host countries. There has been and will continue to be legal and political resistance to the application of unmanned or autonomously operated vehicles, especially those that incorporate lethal payloads (Anderson and Waxman 2013). UUV systems need to be designed with fail-safe mechanisms to prevent unintended activations. They also should comply with environmental standards to the maximum extent possible. Addressing these concerns early and often in the systems engineering process can reduce complications later in the system life cycle.

B. PROBLEM DEFINITION PROCESS

The first block in our tailored waterfall process (Figure 3) is Problem Definition. Both a thorough literature review and stakeholder analysis were finished prior to completing the problem definition in order to remove as many biases and misconceptions as possible.

The project team's original tasking was to design a system of UUVs that will provide an operational undersea force available for tasking over a range of mission by 2024. What this tasking lacked was the context for why UUVs are required in the first place. Through our research, the project team determined that UUVs have the ability to execute new mission sets and extend the functionality of current and future platforms in order to maintain our maritime superiority in challenging A2AD environments.

Derived Problem Definition

Potential adversaries continue to acquire and develop sophisticated multi-layered A2AD systems. In order to maintain our maritime superiority, the United States must continue to field systems that have the specific capability to enter into and defeat these A2AD environments.

Increasingly complex A2AD environments require stealthy vehicles to execute critical mission sets. For over half of a century the United States Submarine Force has primarily taken on the task of exploiting A2AD environments, but the U.S. faces significant challenges as the total numbers of mission-ready submarines are reduced. Just

as UAVs have revolutionized the air domain, UUVs have the potential to act as affordable force multipliers in the undersea domain, while greatly reducing risk to high value units and personnel conducting critical mission sets in A2AD environments.

C. MAPPING OF STAKEHOLDER NEEDS

Traceability throughout the system engineering process ensures that stakeholder effective needs are met by the designed system of systems. Table 3 provides a comprehensive list of system needs that can be traced back to individual stakeholder classifications. This list includes not only the effective needs of stakeholders but also the needs presented by the derived problem definition. System requirements generated during the systems engineering process are then mapped back to these needs.

Table 3. Stakeholder to Needs Mapping. System effective needs are generated from the thorough analysis of stakeholder documentation, interviews, and derived primitive needs. Effective needs are used later in the systems engineering process to aid in the development of system requirements.

NEED	STAKEHOLDER GROUP	SYSTEM NEED
2.1	1.0 Investors	Systems need to support undersea dominance.
2.2	1.0 Investors	Systems need to be able to enter into and defeat enemy A2AD environments.
2.3	1.0 Investors	Systems need to incorporate an operational organization and structure.
2.4	1.0 Investors	Systems need to meet mission-appropriate endurance requirements.
2.5	1.0 Investors	Systems do not need to consider nuclear propulsion methods.
2.6	1.0 Investors	Systems need to be cost effective.
2.7	1.0 Investors	Systems need to be implemented in a time-phased approach.
2.8	1.0 Investors	Systems currently developed that can make an immediate impact need to be placed into operational service.

NEED	STAKEHOLDER GROUP	SYSTEM NEED
2.9	2.0 Developers	Systems need to utilize COTS components and platforms when feasible.
2.10	2.0 Developers	Systems need to incorporate modular system designs.
2.11	2.0 Developers	Systems need to survive in expected maritime operating environments.
2.12	2.0 Developers	Systems developers need to receive adequate compensation.
2.13	3.0 Infrastructure Providers	Systems need to be transportable by current and planned operational platforms.
2.14	4.0 Infrastructure Supporters	System transportation methods need to be integrated onto stealthy platforms.
2.15	5.0 Operators	Systems need to be safely deployed/recovered from host vessels.
2.16	5.0 Operators	Systems need to be safe to operate.
2.17	5.0 Operators	Systems need to be safe to maintain.
2.18	5.0 Operators	Systems need to be stealthy.
2.19	5.0 Operators	System launch and recovery needs to mitigate host platform vulnerability.
2.20	5.0 Operators	Systems need to be relatively easy to operate.
2.21	5.0 Operators	Systems need to exhibit high degrees of the “ilities.”
2.22	5.0 Operators	Systems need to utilize USN sailors for operation and organizational level maintenance.
2.23	6.0 Customers	Systems need to be able to be deployed rapidly worldwide.
2.24	6.0 Customers	Systems need to account for operational expendability.
2.25	6.0 Customers	Systems need to account for information assurance.

NEED	STAKEHOLDER GROUP	SYSTEM NEED
2.26	6.0 Customers	Systems need to operate with minimal manning.
2.27	6.0 Customers	Systems need to be able to conduct various missions using open architectures.
2.28	6.0 Customers	Systems need to communicate between unmanned and manned system effectively.
2.29	6.0 Customers	Systems need to incorporate covert communication methods.
2.30	6.0 Customers	Systems need to conduct data collection and dissemination.
2.31	6.0 Customers	Systems need to incorporate autonomous technologies.
2.32	7.0 Partners	Systems need to interface with joint operating environments.
2.33	8.0 Suppliers	Systems need to incorporate efficient logistical support.
2.34	9.0 Competitors	Systems need market competitors to incentivize technology advancement and affordability.
2.35	10.0 Adversaries	Systems need to minimize susceptibility to enemy countermeasures.
2.36	10.0 Adversaries	Systems need to operate with minimum impact to the environment.
2.37	10.0 Adversaries	Systems do not need to consider chemical, biological or radiological weaponization.
2.38	10.0 Adversaries	Systems need to minimize collateral damage.

Chapter Summary

This chapter summarizes the significant stakeholder interactions that have taken place over the course of the study. These interactions led to the derived problem statement that focuses the project efforts on conducting operations in an A2AD environment. The needs analysis also identified the following key enduring capabilities that are required for successful operations in these challenging environments:

- Endurance
- Stealth
- Lethality
- Effective sensors
- Mission flexibility
- Communications
- Self-sufficiency

Project expectations from our primary stakeholders are also clarified through several site visits and personal interviews. Over the duration of the study, SEA-19A team members participated in many demonstration, symposium, conference, and program review related to unmanned undersea technologies.

With a strong fundamental understanding of project expectations and current UUV capabilities, the team had to scope the project to reasonable expectations based on project duration, and available manpower. Results of the concepts, attributes, and characteristics that are both included and not included in the capstone report are explained in detail in the next chapter.

III. SCOPE

A. SCOPE METHODOLOGY

The focus of this study is to determine UUV contributions to the future force structures of the USN. These contributions are of particular interest due to the fact that senior naval leadership expects the full integration of UUVs into the fleet by 2024. To enhance the overall effectiveness of the study, the project team defined system characteristics that are within the scope of the project and those that are outside of the scope. Utilizing the iterative systems engineering process, the team initially defined what to include/exclude for the project and then conducted more detailed scoping after completing the stakeholder analysis described in Chapter II. As we continued to progress through the waterfall process, the team conducted further scoping based upon applicable undersea missions and the dimensional analysis of current and planned UUVs.

The SEA-19A project team believes that the scope of this project is both grounded in reality yet flexible enough to envision systems or systems-of-systems that can bring revolutionary capabilities to the undersea warfare domain.

B. IN SCOPE

Initial project scoping comes from the problem statement which focuses on operations in an A2AD environment. This is an environment where undersea dominance and the associated capability of stealth offer the ability to penetrate layered enemy A2AD defenses which consist mainly of weapons such as anti-ship cruise missiles (ASCMs), anti-ship ballistic missiles (ASBMs), submarines, mines, and air defenses. The A2AD operating environment is assumed based upon the mass proliferation of these weapons throughout the world and through a threat analysis of potential adversaries that possess the capability of effectively deploying this genre of maritime weaponry. The Air-Sea Battle concept, generated by General Schwartz and Admiral Greenert, also identifies the A2AD environment as one of the primary threats to American power projection (Greenert and Schwartz 2012).

The undersea warfare domain is unique, due primarily to significant environmentally-based complications with undersea command and control and communications. Various platforms offer differing levels of capability to overcome these challenges. A system-of-systems approach is used to determine which platforms are best utilized. All UUV host platforms are considered as a system-of-systems, but in terms of major combatants, the focus of our study is on submarines and surface ships as potential launch platforms. UUVs of all types are considered, to include varying levels of autonomy and remotely operated vehicles that are either tethered or untethered. Expendable and reusable UUVs are also considered in the study. Other manned and unmanned platforms such as aircraft, UAVs, Unmanned Surface Vehicles (USVs), as well as other unmanned sensors are given consideration as support elements of undersea dominance.

In development of the concept of operations, all physical conditions of the maritime operating environment are considered with special emphasis given to the most likely operating environments. These likely operating environments are derived from existing force deployment locations as well as developing regions of strategic importance in the global commons. The physical elements considered include, but are not limited to, such factors as temperature, pressure, water depth, water salinity, sea state, turbidity and visibility.

The 2020 to 2024 timeframe and immediate implementation of a system is a main driver in the level of technological maturity that is included for analysis. Primarily, only technologies that have reached Technology Readiness Level Four (TRL-4) are considered for inclusion. Per the U.S. DoD Technology Readiness Assessment Guidance, TRL-4 is defined as component and/or breadboard validation in a laboratory environment (Assistant Secretary of Defense for Research and Engineering 2011). Technology not currently at the breadboard validation level or higher is unlikely to have the capacity for incorporation into a system or system of systems in the near term at a reasonable cost. However, any technologies below TRL-4 that show significant promise of bringing critical capabilities to UUVs within the scoped timeframe may be considered during the analysis of alternatives and are also documented in the future studies portion of this report.

Cost estimation of the proposed system of systems recommended by the team is included in this study. Comparison of cost effectiveness with regard to specific measures of effectiveness (MOE) and measures of performance (MOP) are examined in the recommendation process. All costs, including life cycle cost, are estimated based on current FY13 dollars. Future budget allocations are not considered in the systems engineering process, but have a role in the recommended solution implementation path.

In addition to a focus on the contribution of UUVs to undersea dominance, other elements of existing weapon systems that contribute to future undersea dominance are examined. Recommendations for modification of in-service weapons systems that enhance undersea capabilities or adoption into an unmanned weapon system are considered. Leveraging existing capabilities in new and unique manners has the ability to transform and extend the functionality of current and future platforms.

Nonmaterial solutions and recommendations have an important role to play in undersea dominance and have been incorporated into this study where feasible. Such solutions include changes and modifications to doctrine, organization, training, manpower, leadership and education, personnel, and facilities referred to commonly as DOTMLPF.

To provide structure to the study all missions listed in the United States Navy *UUV Master Plan* are given initial consideration as viable missions for UUVs. This list is augmented by new mission sets as a result of stakeholder analysis and critical group assessment of the A2AD operational environment. After starting with this initial study framework, specific missions were excluded from the study. The 2024 timeframe and technological limitations are the primary driving factors on missions excluded from our analysis. Due to its importance to our study, specific information on the missions analyzed and scoped is provided in the mission scoping section of this chapter.

C. OUT OF SCOPE

One of the main goals of this study is that it be grounded in the reality of both the present and near-future force structure of the United States Navy. Developmental naval platforms, to include submarines and surface combatants, which have not yet reached

developmental test and evaluation (DT&E) are not considered in the analysis. The goal of this project is not to develop a major manned or unmanned weapon system from scratch, but rather to incorporate manned and unmanned technologies that are already in service or proposed in the force in the near term. This project is not designed to provide detailed architectural or software designs of potential developmental UUVs, but rather to provide critical elements of systems-level design that facilitate UUV operational success.

Regarding UUV recommendations, certain aspects are not examined. In CONOPS development, a United States only force structure is assumed. Although communication, interaction, and cooperation with multi-national forces will be required in future naval operations, it is assumed that only current platforms in the inventory of the United States Navy will communicate with and exercise command and control over the proposed UUV systems. Future work may address the interoperability standards required for multi-national use, but for the purposes of this study it is outside the scope.

Several specific technologies are also excluded from consideration including low power nuclear reactors or radioisotope power generation systems. Although these systems are highly capable and have been demonstrated in space system applications, the project team does not feel that an unmanned nuclear reactor or radioisotope power generation system on the planet's surface is politically acceptable in the United States or the international community. Utilization of these power sources in unmanned vehicles also violates key tenets of the Naval Nuclear Propulsion Program (NNPP) such as the need for human oversight and supervision. In the event of a mishap or system compromise, there are potentially catastrophic dangers to personnel, the environment, and the national security of the United States and its allies (U.S. Department of Energy 2013).

The inventory of unmanned and "smart" weapons will continue to increase as the growth of computing power progresses. The enhanced autonomy capabilities that this increased computing power brings to the undersea domain are explored in this project, however, any additional moral and ethical considerations are not within the purview of the project. Varying levels of autonomy are discussed in this project but no moral attachments or interpretations are made. Such interpretations of legality in relation to the

use of force and autonomy are currently unresolved and reside with the civilian leadership of the United States government as well as the international community (DoD Defense Science Board 2012).

D. MISSION SCOPING

The project scoping statement is not meant to be an all-inclusive list of what is considered within the project, but rather a framework that guides the study. The iterative systems engineering process is used to define and scope the mission sets analyzed by the team. Initially, all mission sets in the *UUV Master Plan* are considered as viable mission sets:

1. Intelligence, Surveillance and Reconnaissance (ISR)
2. Mine Countermeasures (MCM)
3. Anti-Submarine Warfare (ASW)
4. Inspection / Identification
5. Oceanography
6. Communication / Navigation Network Nodes (CN3)
7. Payload Delivery
8. Information Operations (IO)
9. Time Critical Strike (TCS)
10. Barrier Patrol (Homeland Defense, Anti-Terrorism / Force Protection (ATFP))
11. Barrier Patrol (Sea Base support)

To scope the breadth of the project, these missions were reorganized based upon functional characteristics required to execute the missions. Missions that exhibited similar functional traits were combined to reduce the complexity of analyzing and modeling each mission individually. To further scope down the missions to be analyzed, the project team analyzed which missions would have the greatest probability of suffering from technology development limitations, and which missions had the least likelihood for successful operational integration within the given 2024 timeframe. Final mission

exclusions were made based on the relevancy of the missions in an assumed A2AD environment. Final mission scoping resulted in the examination of the following four mission areas:

1. Intelligence, Surveillance and Reconnaissance (ISR)
2. Mine Countermeasures (MCM)
3. Offensive/Attack Operations
4. Information Operations (IO)

ISR missions are a top priority in undersea dominance. Other mission sets that are incorporated into the ISR category are inspection/identification and oceanography due to their functional similarities. The offensive/attack mission set comprises ASW, ASUW, payload delivery, and offensive mining operations, all of which involve the delivery of a payload effector; whether it is a weapon, sensor, or support equipment. MCM missions encompass all aspects of the location, identification, and neutralization of undersea mines. IO is a unique mission set with unique functions, such as military deception (MILDEC) and submarine decoy operations, which can be heavily influenced by advanced UUV technologies.

The CN3 mission set is not within the scope of this study since communications network development and implementation represents an entirely separate study. The project team examined communications but not specifically the development of mobile or emplaced communications systems. Professor Joseph Rice and the Sea Web program at Naval Postgraduate School, and other industry partners, continue to conduct extensive research on undersea communications networks. UUVs may serve an important role in this mission area as undersea communication technologies continue to evolve in the future.

Time critical strike is a unique and required mission set in modern warfare. The current submarine force offers proven and capable platforms to conduct TCS on critical targets with little or no warning to the enemy. From a submerged platform, the Tomahawk missile is the primary weapon system capable of executing TCS missions. The project team examined the specifications necessary for a UUV to conduct TCS

missions with a Tomahawk missile and determined that the length and weight are prohibitively large for a UUV. Each Tomahawk missile is over twenty feet long and weighs approximately 3,300 pounds (Naval Air Systems Command 2013). A payload section of greater than twenty feet would likely require a propulsion section of commensurate length. This would lead the overall vehicle size to be much larger than any currently planned UUV platform. TCS is best performed by the current submarine and surface fleets and is excluded from the study. Although excluded from our study, our project team does acknowledge that small scale TCS, utilizing smaller munitions, may be feasible from a UUV within our 2024 timeline, and will be included in the offensive operations mission analysis.

Barrier patrol for both homeland defense/anti-terrorism force protection (ATFP) and sea base support is outside the scope of this study. The ATFP mission is either better performed by fixed sensors or other systems such as USV's since there is essentially no requirement for stealth. Barrier patrol UUVs for sea-based support would be required to delouse operating areas ahead of a Carrier Strike Group (CSG) or Expeditionary Strike Group (ESG). This mission set requires significant speed and endurance capabilities to advance at the same rate as the units it is defending. These speed and endurance requirements suggest that this mission is best executed by the SSN force. However, both of these missions are essentially ASW missions and could conceivably be performed to a certain degree by the alternatives analyzed for offensive/attack missions.

E. DIMENSIONAL SCOPING

An upper bound on the size of UUVs being considered for this study is also considered. To determine a maximum size, a basic transportation analysis is conducted to examine vehicle size in the context of transportation system limitations and a simulation to examine the time required for a UUV to deploy to a target area. This transportation analysis utilized the dimensions and weights associated with the Deep Submergence Rescue Vehicle (DSRV) and the Advanced Seal Delivery System (ASDS). Details of this analysis are included in Appendix B.

Based on the results of the transportation analysis and the weight/size limits associated with current transportation methods, our project team scoped the maximum

bound for UUV size to those that can be deployed from an LCS without significant alterations to the ship. There is no minimum size requirement.

Additional dimensional analysis was conducted to categorize size classes of UUVs for endurance vs. size modeling, which is utilized extensively in the analysis of alternatives. This analysis resulted in three broad categories of UUV size that are considered. The three classes of consideration from largest to smallest are:

1. LCS compatible
2. SSN compatible via ULRM
3. Vehicles less than or equal to 21 inches in diameter

The LCS is specifically designed to be a forward-deployed platform capable of high speed, littoral operations. Mission modules for the ship are currently being produced that utilize one of the largest UUVs, known as the Remote Multi-Mission Vehicle (RMMV). The RMMV dimensions (United States Navy - RMMV 2012) are:

- Length: 23ft
- Diameter: 4ft
- Weight: 14500lbs

These parameters are not given to restrict potential design specifications, but to give a general magnitude of the size of UUV capable of being deployed or retrieved from an LCS. For this study the heaviest UUV being considered is 18000 lbs. which corresponds to the LCS handling crane weight limit (Pierzga 2012).

Both SSGNs and Virginia Class SSNs are expected to be outfitted with the tactical ULRM. In this case the tube length and diameter of the Vertical Launch System (VLS) physically constrain the dimensions of the UUVs. Notional dimensional restrictions for UUVs operating with ULRM capable submarines (U.S. Director of Undersea Forces – Appendix A 2012) are:

- Length: 20ft
- Diameter: ~60in
- Weight: 30000lbs

UUVs that are less than 21 inches in diameter can be deployed from almost any naval platform. This size class of UUVs is the most widely available and researched variant and will factor heavily into the future UUV force structure. The maximum 21-inch diameter restriction on this class is determined from the standard submarine torpedo tube diameter.

Chapter Summary

This chapter provides the critical elements of consideration that will be analyzed throughout the remainder of this report. Just as important, it also provides ample justification for why many elements are being omitted.

In the context of the assumed A2AD operating environment the following four missions will be analyzed throughout the remainder of the report:

- Intelligence, Surveillance and Reconnaissance (ISR)
- Mine Countermeasures (MCM)
- Offensive/Attack Operations
- Information Operations (IO)

Different UUV sizes will also be analyzed for mission effectiveness. Operations from both the LCS and submarines equipped with ULRMs provide the approximate LDUUV dimensions for consideration. 60” is the anticipated largest diameter UUV compatible with the ULRM and is therefore the largest diameter considered in this study. Maximum diameter and length restrictions for LCS operations have yet to be determined. 21” and smaller UUVs are assumed to be operable from practically any platform.

Other important considerations within the scope of the project are to explore the effectiveness and cost of both expendable and recoverable UUVs. Tethered or autonomous operations are another important factor to consider.

The next chapter leverages background research and stakeholder analysis, to decompose the essential functions necessary to perform undersea missions, which are then used to identify many of the critical system level requirements to be analyzed in modeling and simulation.

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IV. FUNCTIONAL ANALYSIS

A. FUNCTIONAL ANALYSIS APPROACH

Functional analysis is accomplished to determine the UUV systems' underlying component functions. Specifically, the objective of this analysis is to capture the primary functions needed to execute undersea missions. Using the mission based approach, individual mission functional decompositions are completed on the four scoped UUV mission areas identified in Chapter III. As expected, the majority of the mission specific component functions are very similar to one another. This facilitates the development of the top-level functional hierarchy for a multi-mission capable system to perform undersea missions shown in Figure 7.

Testing the continuity and completeness of the functional hierarchy is accomplished by sequencing functions, with respect to time, in a Functional Flow Block Diagram (FFBD) illustrated in Figure 8. After several iterations, functional gaps can and should be identified and appropriately filled.

It is difficult to see the complex workings of a technical system using just the top-level functional hierarchy and FFBD. Lower-level, or more detailed, functional decompositions and FFBDs are provided in the sections that follow, in order to analyze UUV system characteristics and aid in system level requirements generation. Ultimately, any selected UUV systems need to perform the functions necessary to complete its respective mission. Finally, traceability of the analysis of alternatives to functionality is used to ensure that candidate UUV systems perform the necessary functions to meet specific mission requirements.

B. TOP-LEVEL FUNCTIONAL ANALYSIS

1. Top-Level Functional Decomposition

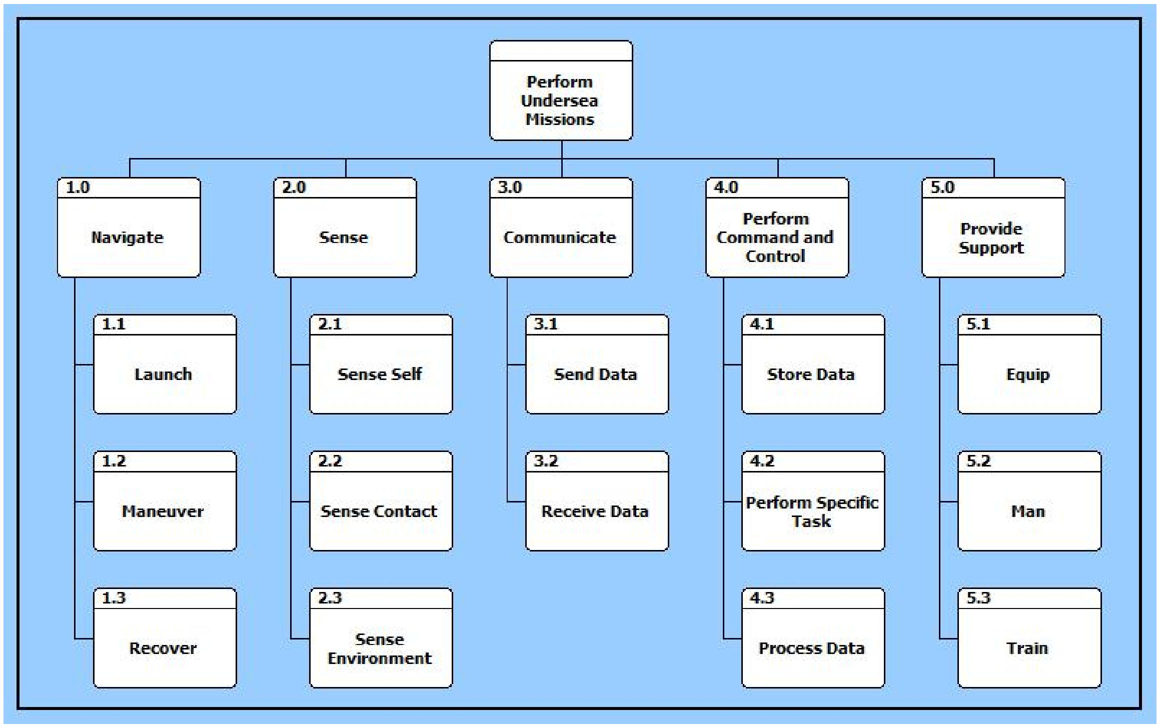

Figure 7. Top-Level Functional Hierarchy. Functions are identified using both top-down and bottom-up methods in an attempt to capture all the primary functions required for the system to maintain sustained operations in the intended environment.

This hierarchy not only describes the primary functions of an individual UUV, but also forms the framework from which the larger system of systems can function. A force structure comprised of many UUVs also performs all of the same functions. Visualization and interpretation of the hierarchy is intended to be generic in both nature and application to all UUV systems and force structures. To provide clarity, the five primary sub-functions of the "Perform Undersea Missions" block are defined. General descriptions of second level sub-functions are also provided to facilitate functional understanding.

2. Top-Level Functional Definitions

Navigate (1.0) Function: This function describes the systems physical movement through an undersea environment. The three sub-functions of the *Navigate* (1.0) function capture the notional navigation life cycle of a retrievable vehicle. The *Launch* (1.1) sub-

function describes the initial movement away from the host platform. The *Maneuver* (1.2) sub-function describes the transit and station-keeping phases. The *Recover* (1.3) sub-function describes the vehicle recovery phase. It is important to highlight that not all UUV systems may require the recovery sub-function. Additionally, the launch and recovery functions do not necessarily have to be performed by the same unit.

Sense (2.0) Function: This function describes the use of sensors for data collection and internal/external monitoring. The *Sense Self* (2.1) sub-function senses parameters vital to the internal operation of system components such as battery life, water/air intrusion, speed, etc. The *Sense Contact* (2.2) sub-function senses contacts of interest above and/or below the waterline depending on mission configuration. The *Sense Environment* (2.3) sub-function senses environmental factors, such as temperature, depth, pressure, etc., through which the system travels.

Communicate (3.0) Function: This function describes both internal and external data transfers. The *Send Data* (3.1) and *Receive Data* (3.2) sub-functions describe internal and external data transfers. The internal transfer captures the information exchange between individual components, such as between a receiver terminal and a decryption unit. The external transfer describes information exchange through an external medium between another platform and the vehicle.

Perform Command and Control (4.0) Function: This function describes the processes internal to the system associated with analyzing data and making decisions that drive the actions the system will perform. The *Store Data* (4.1) sub-function describes the system ability to store data received into the system. The *Process Data* (4.3) sub-function describes the ability to drive the system actions required by data received or internal data instructions. The *Perform Specific Task* (4.2) sub-function refers to the execution of designed mission parameter, such as visual/acoustic ISR collection, mine identification, launch offensive weapon, etc.

Provide Support (5.0) Function: This function describes the mechanisms used to keep the system operational. The *Equip* (5.1) sub-function describes all equipment, spare parts, and supplies necessary to conduct undersea missions. The *Man* (5.2) sub-function describes all the personnel required at the depot, intermediate and organizational levels

necessary to execute the system life cycle. The *Train* (5.3) sub-function describes the training required for leadership, operators and maintenance personnel.

3. Top-Level Functional Flow

As mentioned in the Functional Analysis Approach (Chapter IV. A), the FFBD (Figure 8) is used primarily to identify gaps in the functional hierarchy and also to provide a visualization of the functional process used to perform undersea missions with UUVs.

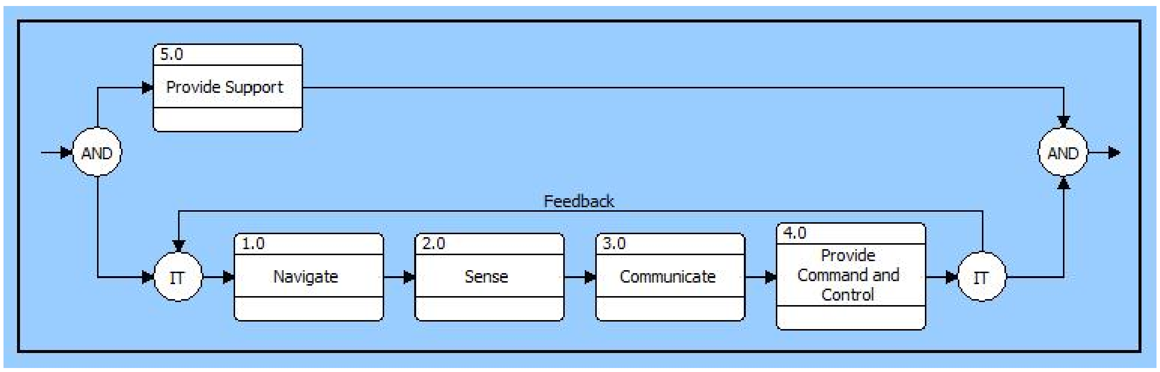

Figure 8. Top-Level Functional Flow Block Diagram. First, the system must be able to physically move through an undersea environment. Then to be of any usefulness the system must gather data from onboard sensors and eventually be able to communicate the gathered information to system users. The system must also be able to react and make decisions based on designed mission. Throughout the entire process, support is required for sustained operations.

Upon completion of the top-level FFBD, there are two primary functions that are not linear in regards to execution. The *Support* (5.0) function was required in parallel throughout the process and the *Command and Control* (4.0) function acts iteratively, in that it can process data and re-initiate action of an earlier process. While useful to understand the basic functional process, the top-level FFBD does not provide the complexity necessary to confidently state that all primary functions have been identified. In order to develop a more complete and comprehensive FFBD, detailed sub-functional decompositions are developed.

C. DETAILED FUNCTIONAL DECOMPOSITION

1. Sub-Functional Decomposition

***Navigate* (1.0) Functional Decomposition:**

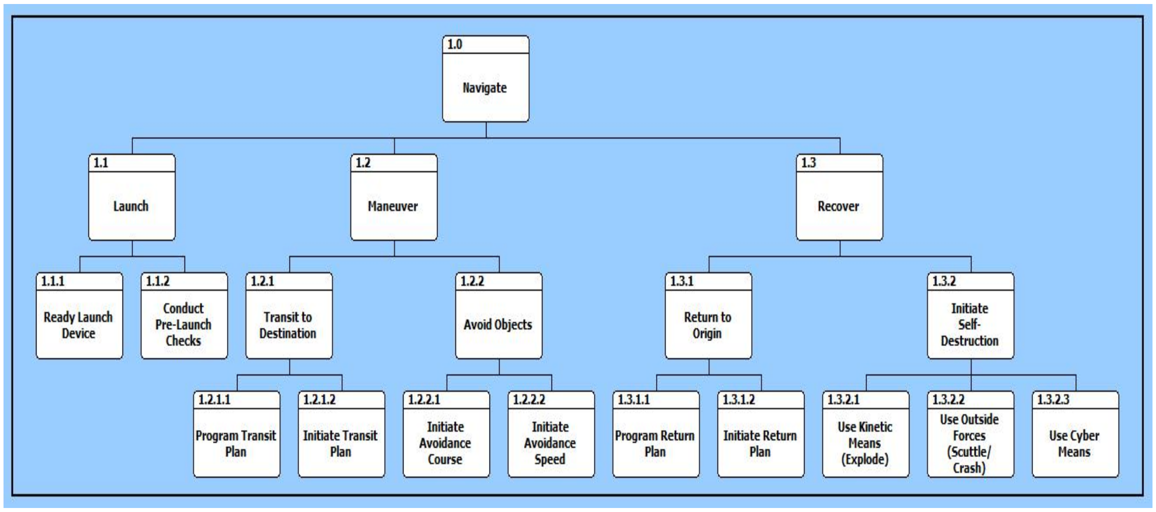

Figure 9. *Navigate* (1.0) Functional Decomposition. The system must be able to depart the launch platform, maneuver as necessary to reach intended destinations, and if required return to a specified area to be recovered.

The *Navigate* (1.0) function is broken down into three major secondary tiers which include the *Launch* (1.1), *Maneuver* (1.2), and *Recover* (1.3) sub-functions. These sub-functions are further decomposed to provide sufficient functional understanding.

Launch (1.1) – This sub-function describes the initial movement of the system from a point of origin or release. In the case of a singular vehicle it would describe the entry of the vehicle into the water and the physical detachment of the vehicle from the host platform.

Maneuver (1.2) – This sub-function describes the transit and station-keeping phases of the system or vehicle, to include object avoidance. For example, a completely autonomous vehicle requires the ability to follow a pre-determined navigation plan, with the additional ability to deviate from a planned track to avoid impeding obstacles. However, remotely operated vehicles may not necessarily require the ability to follow a pre-determined navigation plan. The 4th tier sub-functions essentially describe the rudimentary functions necessary for the system to move in three-dimensional space.

Recover (1.3) – This sub-function describes either the return of the system to the point of origin or the destruction of the system to prevent enemy use. When considering a singular vehicle it can describe the re-capture of the vehicle by the host or other capable platform. It is important to note that the launch platform does not necessarily have to serve as the recovery platform. For systems designed to be expendable, or systems that have been compromised during operations, self-destruction or scuttling of the vehicle has been determined to be an important function to prevent enemy use of critical technologies or sensitive data.

***Sense* (2.0) Functional Decomposition:**

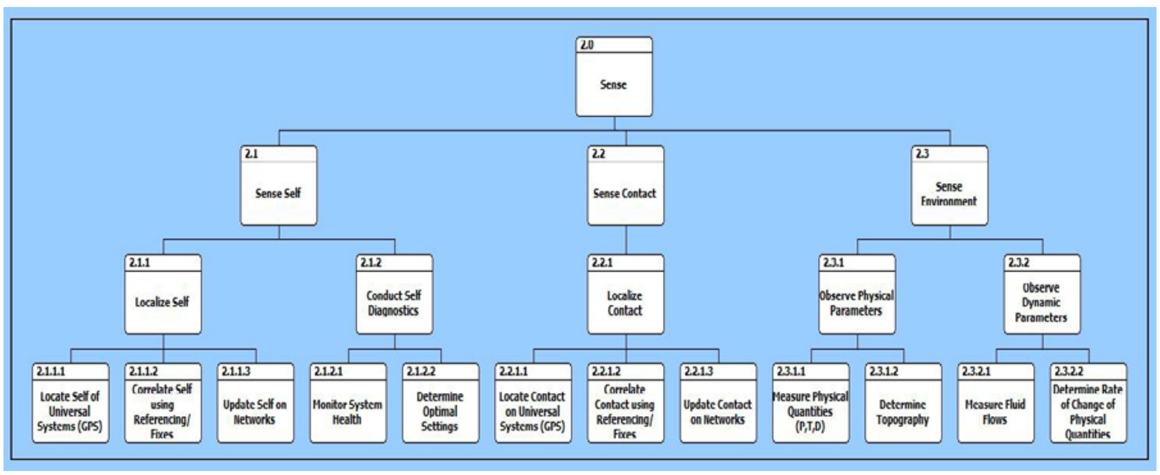

Figure 10. *Sense* (2.0) Functional Decomposition. The system must be able to determine its spatial location in reference to the environment and be able to determine if its subsystems are operating as designed. Onboard sensors need to function as designed to gather required mission data.

The *Sense* (2.0) function is broken down into three major sub-functions based on spatial considerations. The sub-functions of sense contact and sense environment refer to sensing of objects external to the system. Sense self refers to intra-system sensing for monitoring and geo-spatial locating purposes.

Sense Self (2.1) – This sub-function describes the ability to conduct internal monitoring of the system or vehicle components, to include temperature, pressure, ambient moisture, and fluid levels. Other sub-functions identify the various systems used

for allowing a UUV system to spatially locate and position itself as required by the mission.

Sense Contact (2.2) – This sub-function describes the ability of the system to sense an external contact or impeding obstacle. Sensing can be accomplished via active or passive means by leveraging visual, acoustic or electromagnetic technologies. This sub-function also includes the function of localizing contacts in relation to the system.

Sense Environment (2.3) – This sub-function describes the ability to sense the environment in which the vehicle is operating, to include the electromagnetic and oceanic environments. Particular parameters to sense may include pressure, temperature, salinity, acoustic noise levels of the surrounding water, as well as the pervading electromagnetic spectrum external to the water as required by the mission.

***Communicate* (3.0) Functional Decomposition:**

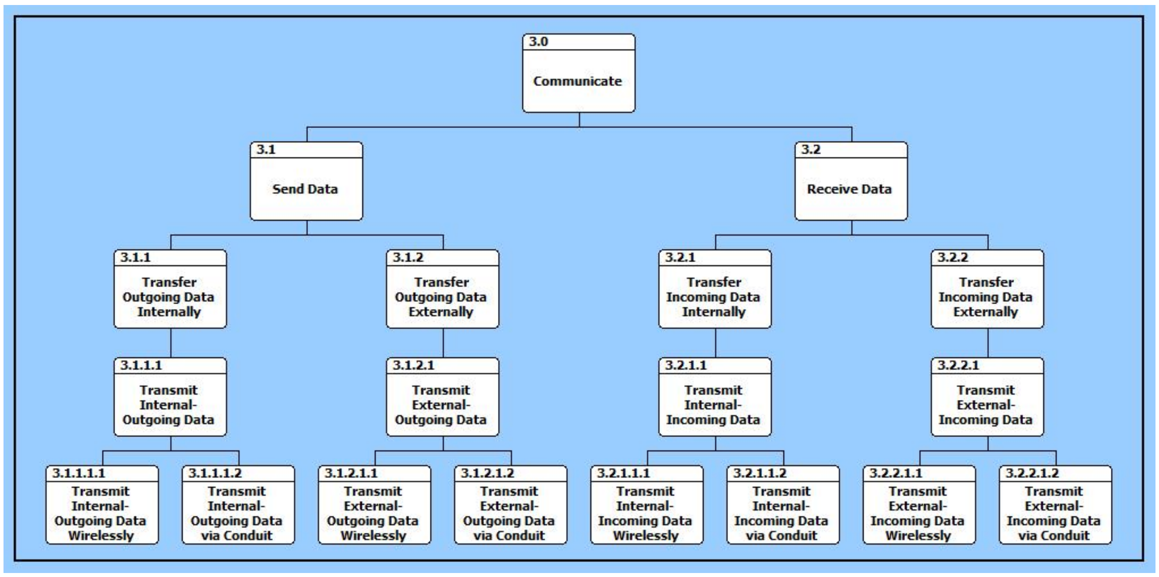

Figure 11. *Communicate* (3.0) Functional Decomposition. Gathered internal and external data must be able to be sent and received through an appropriate medium.

The *Communicate* (3.0) function consists of two sub-functions: *Send Data* (3.1) and *Receive Data* (3.2). Only two sub-functions are defined since the actual movement of data is assumed to occur when these to functions are carried out. These sub-functions are

further broken down to describe data transmission external to the system as well as within the system architecture.

Send Data (3.1) – This sub-function describes the ability of the system to transmit data both internally and externally. Transmission of data can be via a hardwired/tethered or wireless link. In regards to wireless data, information can be transmitted acoustically, optically, or via radio frequency; in the wired case, data can be transmitted via fiber optic cable, copper cable, or other wired mediums.

Receive Data (3.2) – This sub-function describes the ability of the system to receive data both internally and externally. The same wired/wireless links described in *Send Data* (3.1) are available for this sub-function.

***Perform Command and Control* (4.0) Functional Decomposition:**

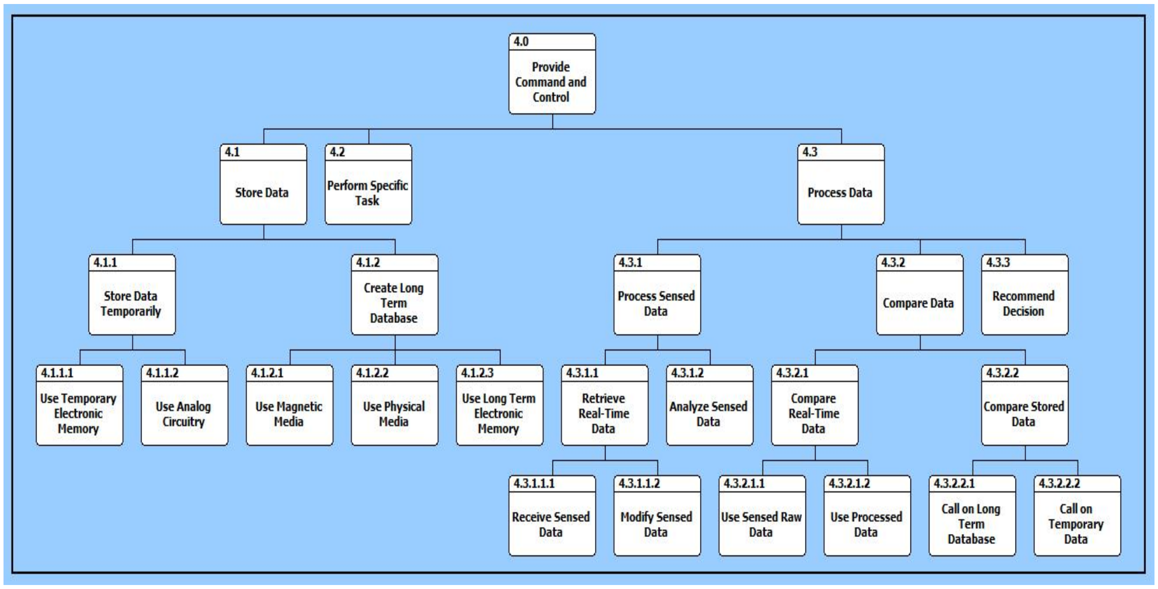

Figure 12. *Perform Command and Control* (4.0) Functional Decomposition. The system must be able to either temporarily or permanently store input data. Processing of the data occurs so the system can make required functional decisions. Finally, the system must be able to perform the mission specific function for which it is designed.

The *Perform Command and Control* (4.0) function comprises three main sub-functions, two of which perform actions involving the processing and storage of data and one which prompts actions specific to the assigned mission.

Store Data (4.1) – This sub-function describes the ability of the system to store information received from a sensor or communication link. This is inclusive of the ability to make those data accessible for use as required by the mission or specific action being performed by the vehicle.

Perform Specific Task (4.2) – This sub-function describes the ability of the system to make decisions based upon processed information to perform a specific task, whether in the direct execution of a mission (i.e., releasing an offensive weapon) or in support of a specific mission (i.e., maneuvering to avoid a contact). Consistent with these two applications is the ability to issue a command to the appropriate components and in the appropriate order to perform a task (i.e., issue signal to propulsion system to increase speed by the appropriate amount to avoid an object).

Process Data (4.3) – This sub-function describes the ability of the system to analyze and execute internal instructions to other system components based on received sensor or communication data (i.e., discern signal of interest from background noise). This sub-function also includes packaging that data in an appropriate manner for transmission or storage.

***Provide Support* (5.0) Functional Decomposition:**

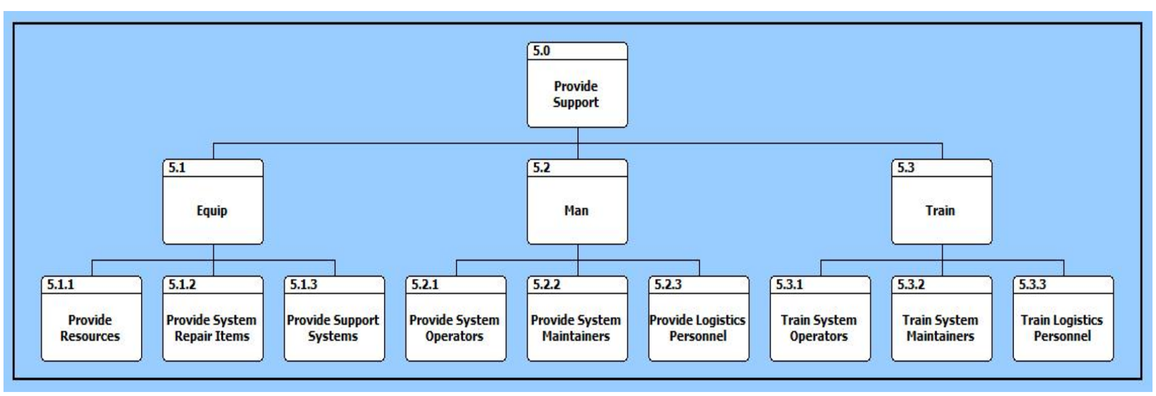

Figure 13. *Provide Support* (5.0) Functional Decomposition. The system requires the appropriate manning, training, and equipment necessary to maintain sustained system operation.

As shown in the top-level FFBD (Figure 8), the *Provide Support* (5.0) function is necessary over the duration of system operation. It is divided into three main sub-

functions, *Equip* (5.1), *Man* (5.2) and *Train* (5.3), that are consistent with DOTMLPF considerations.

Equip (5.1) – This sub-function describes the material support necessary for the system to perform its mission, and includes maintenance requirements, system acquisition strategy, and payload outfitting.

Man (5.2) – This sub-function describes the human support component required for successful operation of the system. This sub-function includes maintainers and operators, and considers the human costs associated with manning UUV squadrons.

Train (5.3) –This sub-function describes the training of leadership, operators and maintainers necessary for successful operation of the system.

2. Detailed Functional Flow

Decomposing the system to third and fourth-tier functions makes it possible to define a more coherent functional flow. The detailed FFBD in Figure 14 provides the complexity necessary to confidently state that all primary functions have been identified in regards to the UUV system of systems.

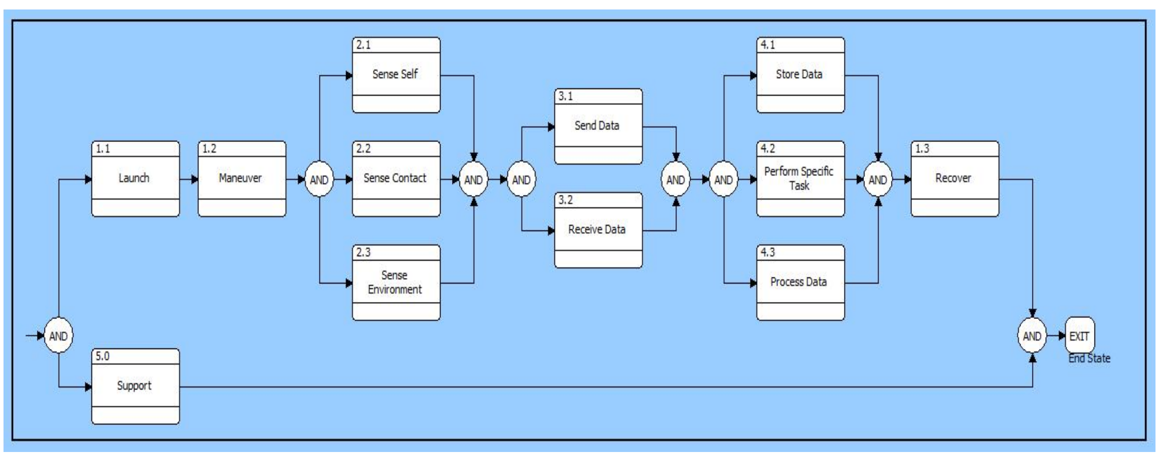

Figure 14. Detailed Functional Flow Block Diagram. Primary sub-functions are included to provide a clear sequential understanding of system functional operation. This FFBD is used to validate the functional hierarchy shown in Figure 7.

The detailed FFBD shows how the system operates under typical conditions. Beginning with launch, the system detaches from its host platform and then transits or

maneuvers to the destination. During the transit, the system will continually sense the environment, scan for objects, and perform internal monitoring and diagnostic processes within the system. Relevant data and information are sent and received between system platforms as required by the mission. Depending on data received, either organically or from outside sources, the system will process the data for immediate decision making or store the data in memory for subsequent data analysis. Once the mission is complete, the system either returns to a retrieval platform or initiates a scuttling sequence.

Chapter Summary

The functional analysis in this chapter provides information on how a baseline UUV system of systems functions. Specific mission functions are intentionally omitted so that preferences towards specific missions do not cloud the essential functions and requirements demanded by all mission sets.

Top level functions required by all UUV systems to perform undersea missions are:

- To Navigate
- To Sense
- To Communicate
- To Perform Command and Control
- To Provide Support

These functions help to identify functional areas that require further technological innovation to effectively execute desired missions. Many of these key enablers are identified throughout the remainder of this report.

As identified in our project scope (Chapter III, Section D), there are four specific missions that are most applicable to our project tasking. The next chapter provides more specific analysis of these mission sets and serves as the UUV Concept of Operations (CONOPS) for the year 2024.

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V. CONCEPT OF OPERATIONS

The concept of operations provides operational mission visualization, accompanied by a comprehensive narrative, of how the project team envisions the future of unmanned undersea warfare by 2024. To increase the value added by this report, the intent is to investigate the applicability and usefulness of UUVs to execute new mission sets and extend the functionality of current and future platforms in order to maintain our maritime superiority in challenging A2AD environments.

Figure 15 provides a visualization of the overall CONOPS for the various missions that UUVs will be capable of performing by 2024. Primary missions include but are not limited to: Intelligence, Surveillance, and Reconnaissance (ISR), Mine Countermeasures (MCM), Anti-Submarine/Surface Warfare (ASW/ASUW) attack operations, and various Information Operations (IO) missions. To provide greater clarity to the overall CONOPS, applicable missions are analyzed individually for their contribution to the 2024 UUV CONOPS.

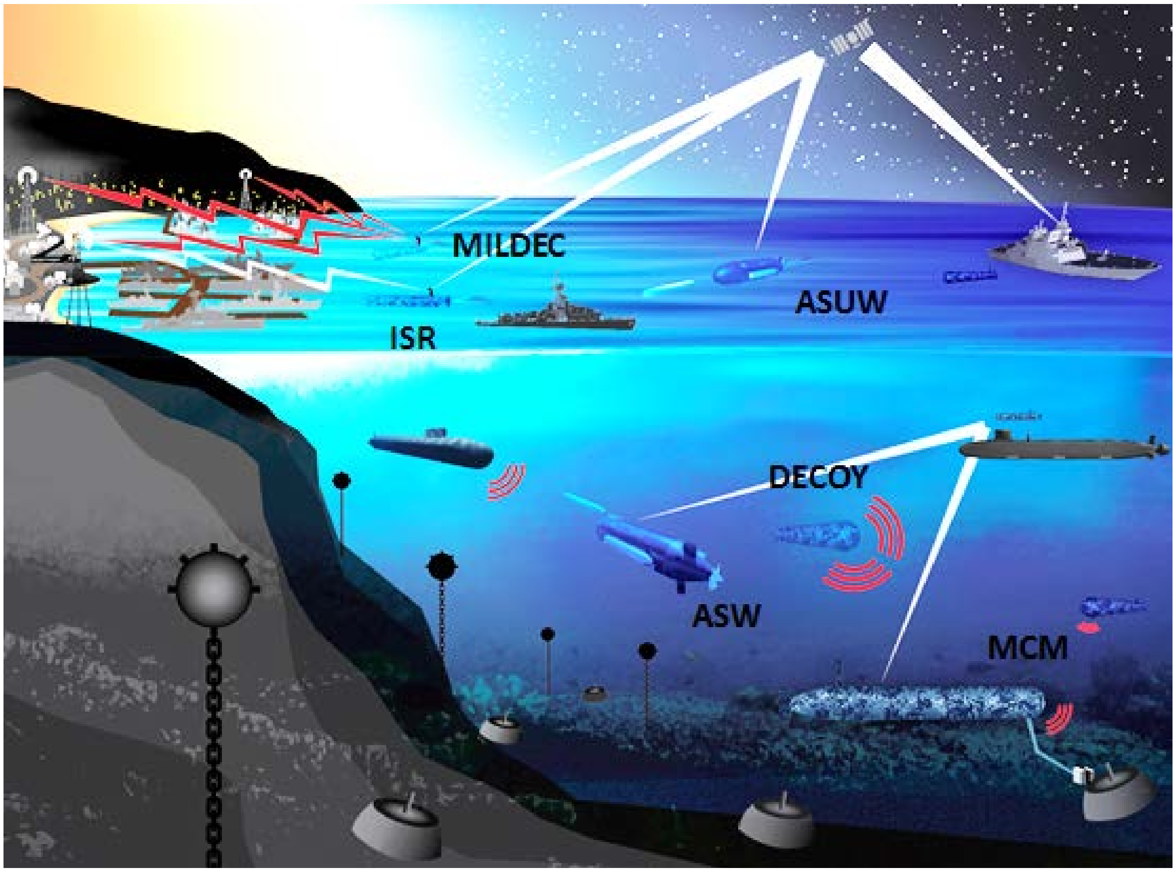


Figure 15. FY2024 UUV CONOPS. Forward operating UUVs provide new capability and risk reduction to high value units operating in potentially hostile A2AD environments, which may consist of layered enemy defenses such as submarines aircraft, ASCMs, ASBMs, and mines.

There are several UUV programs of record, such as those being used for oceanographic research, which are either already operational or will be operational prior to 2024. These programs are already in production or funded with existing CONOPS specifically designed for these programs already in place, and have therefore been excluded from this CONOPS. However, much of the top-level CONOPS is still applicable to many of these systems. Major areas covered by this CONOPS are organization, deployment methods, command and control, communications architecture, and modes of operation.

A. TOP-LEVEL CONOPS

1. Organization

The CONOPS begins with organization. Development of a UUV Squadron (UUVRON) organization, based roughly on existing helicopter squadrons, may be appropriate for initial implementation. Recently, many UAV squadrons have adopted similar organizational structures (Fuentes 2011). Commander Submarine Forces has tasked SUBDEVRON 5 with the responsibility of implementing the initial command organization to support UUV operations. Pending a revolutionary change in standard operating procedures over the next decade, the following paragraphs introduce some notional organization designs that may be used to bring UUVs into mainstream naval operations.

Many UUV platforms are high-technology assets that require specialized maintenance, operations and training of personnel. Notional UUVRONs will operate and maintain a variety of vehicles based upon operational need. Detachments (DETs) from the main UUVRON may embark individual launch platforms and be forward-deployed to operational areas. When required, each DET also provides the requisite amount of manpower necessary to operate and maintain the UUVs embarked. This concept closely resembles how helicopter squadrons embark surface combatants in the USN. This organizational method has proven to be highly successful for decades and could potentially be an excellent model to build upon.

Other UUV platforms, such as those designed for expendability, may only need to be treated as “fire-and-forget” weapons. In this capacity the host platform is only responsible for the launch of the vehicles and may not need specialized operational and maintenance personnel embarked. This concept also opens the door for any type of air, surface, and sub-surface unit to become a UUV host platform.

2. Command, Control, and Communications (C3)

Tactical control of UUVs initially resides with the unit they are embarked upon. The embarked UUV DET has a direct reporting relationship to the host vessel Commanding Officer. The host unit may be tasked by higher authority to utilize the UUV

to conduct specific missions, or to launch the UUV and handover control to other capable units or a master control station (OPNAV Instruction 3120.32D 2012). It is important to note that the degree of external command and control available is directly linked to external communication paths available. This drives the requirement for all untethered UUVs to incorporate some degree of autonomy, when external communication links are lost or degraded.

UUVs primarily operate in one of three modes of operation: manual, semi-autonomous, and fully autonomous; as described in the *Unmanned Systems Safety Guide for DoD Acquisition* (Department of Defense 2007). In manual mode, a human operator gives all or most of the significant commands when in direct communication with the UUV. If communication is lost, the UUV reverts to pre-programmed actions. In this mode of operation a human is almost always in the loop and requires a two-way communication infrastructure. In a semi-autonomous mode, the UUV makes the majority of the decisions autonomously and only communicates with human operators as required by mission programming. In this mode, the human operator issues important command and control decisions in regards to mission execution. Semi-autonomous modes also require a two-way communication infrastructure. In the fully autonomous mode, the UUV has the ability to execute entire mission sets without human operator interaction. Only one-way communication infrastructures may be needed to transmit data collected by fully autonomous UUVs. However, two-way communication infrastructures in autonomous modes may allow for greater mission flexibility and reconfiguration.

A notional UUV should have the ability to communicate with capable platforms when in terrestrial line of sight via hard-wire, radio frequency, optical or acoustic communications methods. Over-the-horizon UUVs should have satellite or other long distance communication capabilities, in order to at least receive or transmit positional data. This capability fosters the ability to control multiple units via a master control station. All UUVs must also be capable of communicating positional data at variable intervals dependent upon mission requirements.

3. Mobility

Notional UUVRON DETs should be capable of air mobility, in order to deploy from the United States aboard strategic airlift aircraft such as the C-5, C-17, and C-130. This allows flexibility for reducing the number of globally pre-positioned units, hereby potentially reducing the total inventory of UUV assets required. The smallest of the aircraft, the C-130 can accommodate the largest variant of UUV system considered in this report. This offers the unique capability to deploy anywhere in the world, in close proximity to where a surface ship or submarine can dock on short notice. Air mobility also provides the potential for airborne launch of UUV variants, thus potentially eliminating the need for conventional platforms to pull into port facilities to embark UUV assets. This transportation concept is analogous to the mobility infrastructure that Special Operations Forces (SOF) utilize to overcome operational constraints, such as the limited availability of personnel and equipment.

Conventional pre-deployment loadouts of many UUV variants onboard host platforms may also be utilized, contingent upon UUV asset availability. This method provides significant UUV capabilities to be immediately available to operational commanders in current areas of interest.

B. MISSION SPECIFIC CONOPS

1. Intelligence, Surveillance, and Reconnaissance (ISR)

The ISR CONOPS includes a broad spectrum of mission sets focused on gathering critical mission data. This mission area is applicable in both peacetime and wartime and comprises a major requirement for current SSN mission assignment. UUVs offer unique capabilities to the ISR mission due to their small size, covert operation, and risk mitigation. The effectiveness of SSNs to perform the ISR mission is limited by the number of platforms available for tasking, water depth, and susceptibility to detection in A2AD environments. UUVs may serve as an affordable force multiplier and also provide an extension of capability to current manned platforms. Figure 16 provides visualization for ISR CONOPS in which UUVs are launched from host platforms, transit to operational areas, conduct the mission, and return to a retrieval platform. Potential missions include

coastal surveillance, signal intelligence (SIGINT), harbor imagery, and undersea terrain mapping.

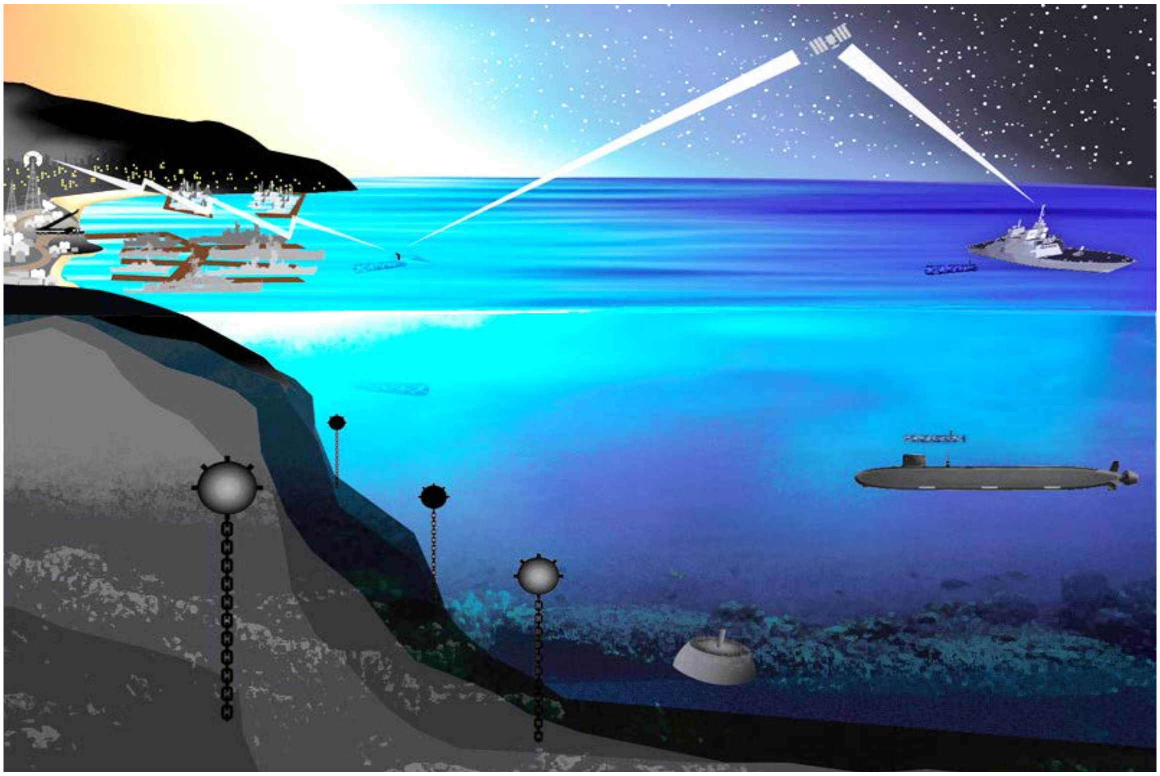


Figure 16. Intelligence, Surveillance, and Reconnaissance CONOPS. UUVs may be used to penetrate into shallow and contested waters to conduct ocean bottom terrain mapping or to conduct imagery and SIGINT operations along an enemy coastline or harbor.

The first design reference mission (DRM) comprises persistent coastal surveillance. A UUV is deployed from a host unit and transits to the area of interest. When on station, it uses a robust sensor suite and advanced autonomous control to avoid obstacles, navigate precisely, and collect data. The targeted data of interest could include radio frequency (RF) signals, visual images, acoustic recording, or environmental data. The UUV must provide this data back to a host unit or controlling station, either by traditional line of sight RF communications, satellite communications, covert undersea acoustic communications, or upon physical connection after vehicle recovery. The data may be transmitted at specified time intervals or event triggers, or in near real-time as the mission scenario requires or permits. This communications profile of the mission depends on the time sensitivity of the data, and accepted level of risk of counter-detection. Vehicle

capabilities, with regard to communication systems, mission endurance time, and available power, also determine an acceptable communications plan.

ISR may also include more specific desired collection such as bathymetric surveys of areas of interest. These missions would not necessarily require the same level of autonomy or communications capability, and could be performed primarily in a pre-programmed fashion with allowances for obstacle avoidance. Collected data could be obtained upon vehicle recovery, subject to time sensitivity of the information. This mission subset is currently conducted by the submarine force, but introduction of UUVs allows for shallower operations and may free up submarines to conduct other pressing missions.

An additional area where UUVs provide a unique capability is in open water surveillance of targets of interest. Adversary naval operations could be observed at closer range than is now acceptable with SSNs or other platforms. The covert posture afforded by the undersea environment offers significant benefits for specified signal collection, tactics observation, and capability assessment. In this context, the UUV would likely return to the host unit for recovery and data transfer, as requiring real time transmissions would unnecessarily risk counter-detection and compromise the covert observation posture.

The ISR mission area requires vehicles with significant endurance and sensor capabilities as well as advanced autonomous control. The UUV must have the necessary endurance to transit an adequate distance to the area of interest in order to decrease the susceptibility of the deploying platform. On-station time must be sufficient to perform the assigned tasking with allowances for the additional power requirements necessitated by obstacle avoidance in congested littoral regions. Sensor payloads must be adequate to capture information of interest with a high degree of accuracy, accounting for the limitations of the autonomous control algorithm to effectively employ the platform.

Without direct human-in-the-loop control, it must be assumed that some collection opportunities may be missed due to the inability of the vehicle to adaptively operate in complex environments. This limitation must be mitigated by capable sensors that can either utilize advanced autonomous target recognition (ATR) software, or be able

to capture large amounts of data with a high degree of accuracy for post-mission analysis by human discriminators. Likewise, collection opportunities may actually increase due to the removal of the human distraction element. For example, if a human operator steers a UUV off the programed course to further investigate a contact, one or more contacts that the UUV could have been sensed, had it remained on the intended course, could slip by undetected. Critical attributes to assess the effectiveness of UUVs to perform this mission include endurance, data storage capacity, stealth, and contact detection capability. Endurance encompasses vehicle range, speed, and available on-station time.

2. Mine Countermeasures (MCM)

The CONOPS for MCM provides limited MCM capability to any ship or submarine that is UUV-capable. This transfers operational risk to UUV platforms and decreases risk to human life by reducing the need for high-value manned vehicles to enter into an area suspected of containing undersea mines.

The CONOPS can further be broken into overt and covert MCM. Overt MCM is defined as openly (i.e., no requirement for stealth) conducting mine countermeasures and neutralization. This type of MCM is applicable when MCM forces are not under direct threat of A2AD environments. The other subset of MCM is covert operations, where friendly forces are under threat from A2AD weapons and stealth is critical to preparing the battlespace for follow-on forces. The covert subset of MCM focuses on locating and identifying mines to establish Q-routes for the safe transit of HVUs. In both mission sets, it is important for the UUV to have extremely high detection rates and low false positive rates. Figure 17 provides visualization for MCM CONOPS in which UUVs are launched from host platforms, transit to operational areas, conduct mine sweeping, localization, and neutralization, and if necessary return to a retrieval platform.

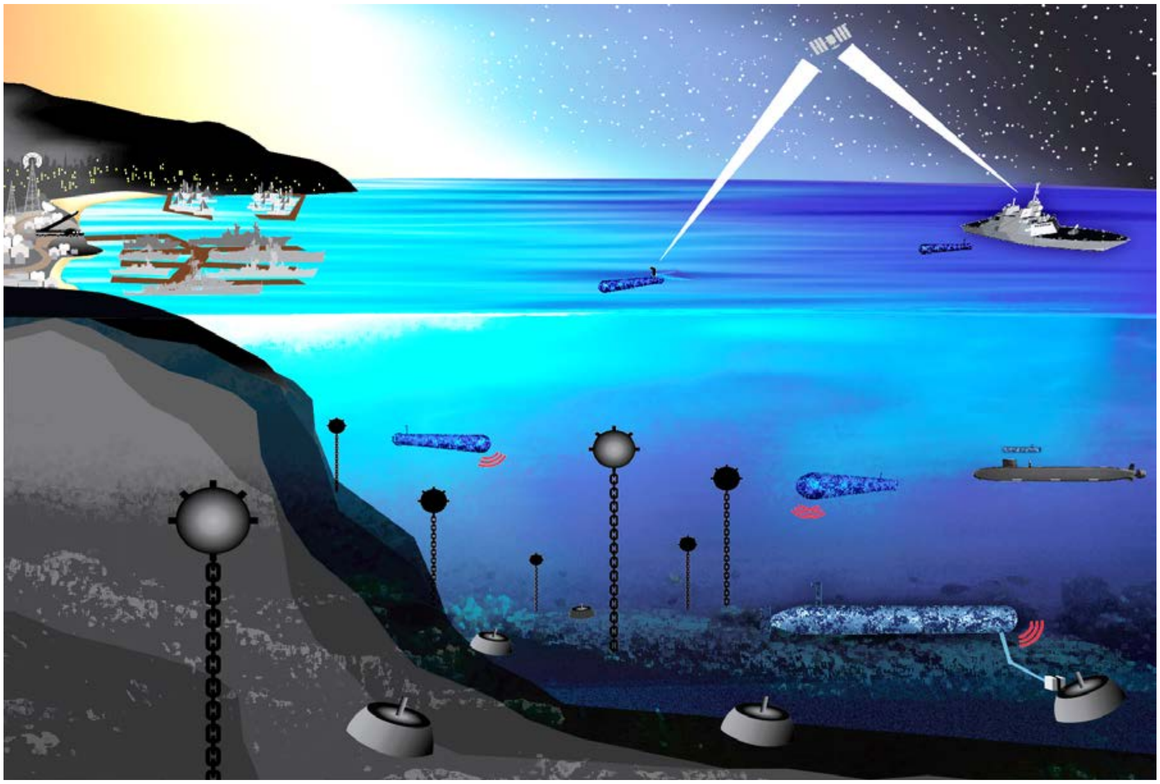


Figure 17. Mine Countermeasure CONOPS. UUVs may be used to map Q-routes through hostile minefields for follow-on forces. Some advanced UUVs may be equipped with mine neutralization capabilities.

Overt mission profiles consist of UUVs being deployed from, e.g., helicopters, surface ships, submarines, or USVs, to a suspected minefield. Once on station, the UUV works cooperatively with other units conducting mine sweeping, localization, and neutralization. Much of the Navy's current MCM UUV focus and analysis is centered on overt MCM to provide a suitable replacement to the aging fleet of MCM ships. Therefore, to provide sufficient value-added by our report, the focus in this study is on covert MCM mission profiles that can contribute to future MCM operations and doctrine.

Covert mission profiles consist of UUVs being deployed from outside enemy RF and acoustic detection ranges in an A2AD environment. Once deployed, the UUV covertly transits to the suspected minefield. The UUV then searches for and localizes enemy mines. Mine locations are then securely transmitted to receiving stations, which are then used to map Q-routes to mitigate undersea mining threats for follow-on forces.

3. Offensive Attack Operations

Offensive UUV operations include coordinated ASW/ASUW attack and offensive mining operations. Attack CONOPS offer a unique expansion of current offensive capabilities, but undeniably pushes the limits of currently available technology, such as UUV size, speed, endurance, and ATR.

Figure 18 provides graphical representation of the offensive CONOPS in which UUVs are deployed from the host platform armed with a torpedo-like weapon that has been modified to engage both surface and subsurface targets. The UUV transits to the operating area and executes its search and destroy mission protocols. In the case of a reusable UUV variant, the UUV exits the operational area and returns to a retrieval platform for rearming and refueling. This concept is very similar to the AUWS concept proposed by the SEA-17B project team. In some cases the UUV and the weapon may be one in the same, in that the UUV is designed as an expendable asset that is launched with no intention of recovery. This concept is very similar to the Mk-48 torpedo conversions programs currently in development (U.S. Navy – ISLMM 2013).

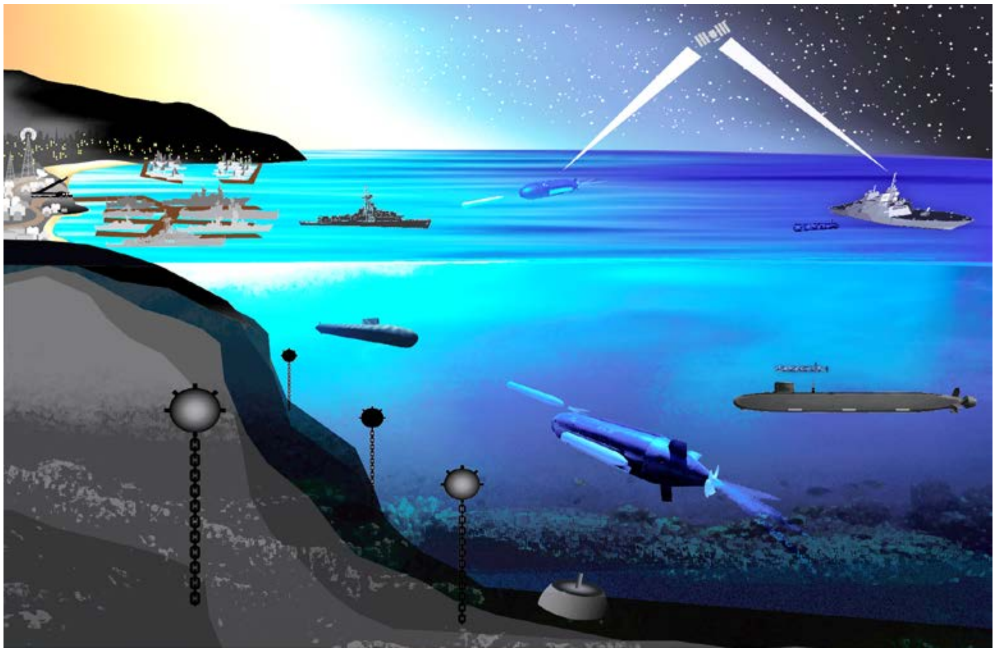


Figure 18. Offensive Attack CONOPS. As shown, UUVs may be used as offensive weapons to assist in coordinated ASW and ASUW operations, acting as sensor or weapon delivery platforms, or both. Other UUVs may be used as effective offensive mining platforms.

Attack vehicle operations require attack UUVs to sense, identify, and attack enemy targets of opportunity. While not required for unrestrained warfare, attack UUVs should incorporate a high degree of target discrimination to prevent unintended targeting and collateral damage to innocent persons and vessels. UUVs may conduct attacks either autonomously or cooperatively with other UUVs, surface ships, aircraft, and submarines.

In a cooperative ASW/ASUW warfare setting, UUVs act as either armed or unarmed sensor platforms that operate in conjunction with surface, air, and submarine units. Cooperative offensive operations effectively extend the combat radius of host vessels through the use of UUVs. Figure 19 represents a notional CONOPS for UUVs operating cooperatively with an LCS, Fire Scout UAV, and other maritime aircraft. The ability for the UUV to act as a forward sensor and sentinel could provide early detection and targeting information for other friendly forces. The UUV could just as easily be utilized as the effecting platform, in that it receives targeting information from other units and launches offensive weapons accordingly.

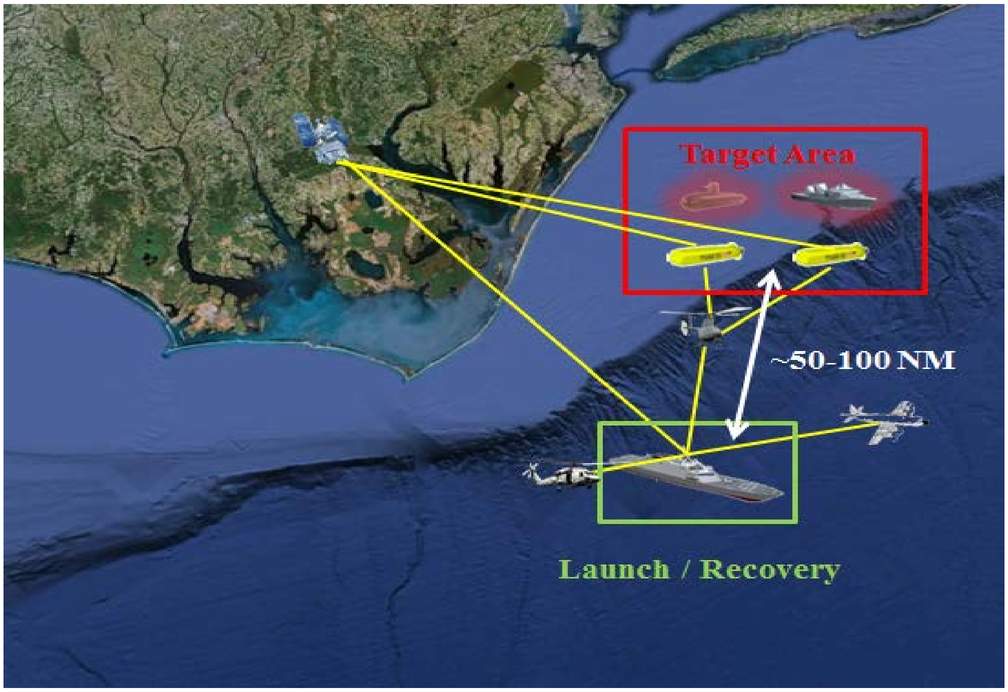


Figure 19. Cooperative Attack CONOPS. UUVs operating in conjunction with other ASW/ASUW assets, such as aircraft, surface combatants, and submarines, to extend operational battlespace effectiveness and awareness.

In an offensive mining role, UUVs are utilized to provide new mining capabilities to the USN. Operations may consist of UUVs stealthily infiltrating enemy harbors and waterways to deliver and place a wide variety of mines. Alternatively, expendable UUVs can simply convert into highly capable mines once they have reached their intended destinations. Figure 20 illustrates UUVs conducting far-forward offensive mining operations. Undiscriminating offensive mining CONOPS can be executed well within the bounds of current technology, but "smart" offensive mining poses significant technical challenges.

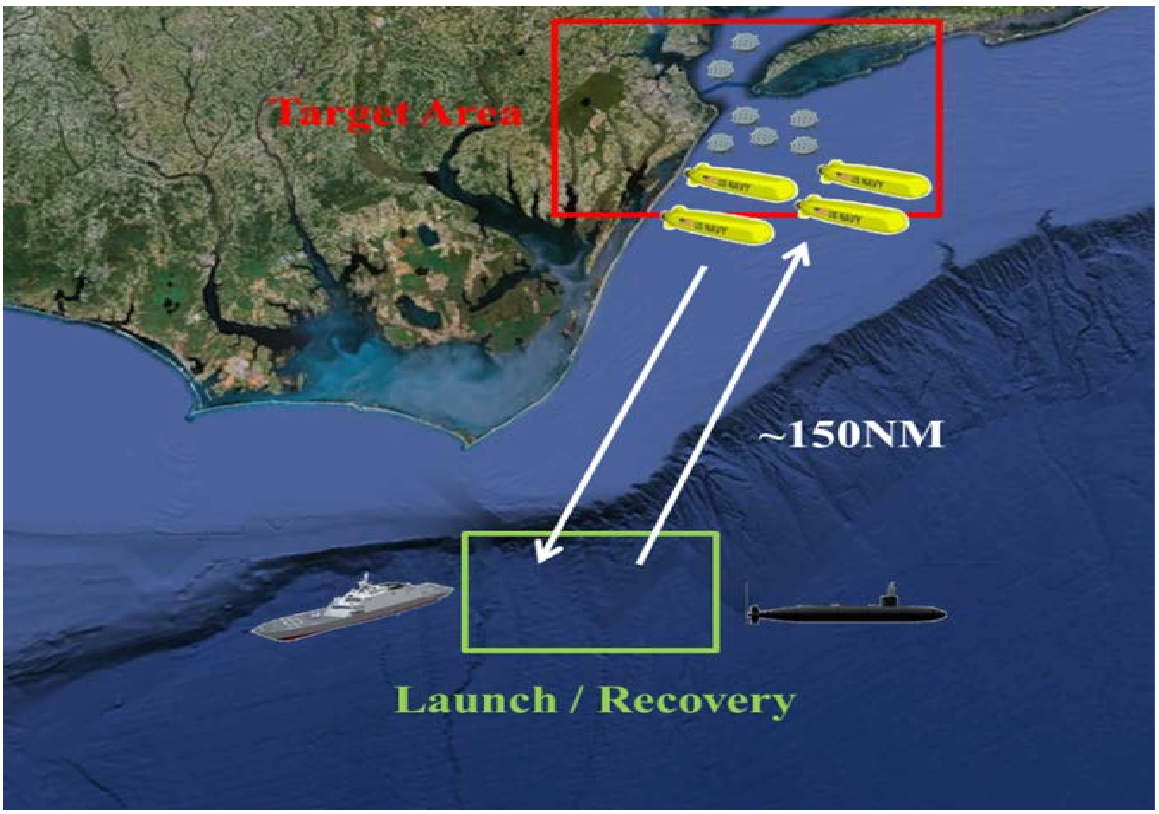


Figure 20. Offensive Mining CONOPS. UUVs may be used as delivery platforms for mines or UUVs may simply convert into sophisticated mines upon reaching intended destinations.

The ability of surface ships and aircraft to effectively deliver mines to decisive locations in an A2AD environment may be questionable and perhaps impractical, leaving the United States with limited options for delivering offensive mines. Current U.S. submarines are capable of conducting offensive mining operations, yet it is a capability

that until recently has rarely been exercised. UUVs may prove to be excellent platforms to fill this critical capability gap, due to their inherent risk reduction and far-forward mining capabilities.

It is important to note that the lines of differentiation between offensive mining and ASW/ASUW attack operations are significantly blurring, and often become one in the same. Technical definitions and classifications of offensive UUV assets seem to be drawing a great deal of attention from the operational and legal communities. In 2013, Dr. Myron H. Nordquist, Professor, Center for Oceans Law and Policy, University of Virginia, led a discussion on the following topic:

> **Status of Unmanned Maritime Systems. Are they vessels? Are they mines? Does the status depend on where, how, and in what manner they operate (e.g., independently propelled, tethered, or immobile)? What is the consequence of the status determination (e.g., sovereign immunity, applicability of various legal regimes)? (Norris 2013)**

While the legal ramifications of such systems are still unclear, it is still important to advance these technologies and be prepared to deploy them in support of United States defense and policy.

4. Information Operations (IO)

The CONOPS for IO incorporates several individual mission sets. These include decoy operations, network exploitation, and psychological operations. Employment of a UUV for cooperative deception also adds a new tactical dimension to USW. Figure 21 provides visualization for IO CONOPS in which UUVs are launched from host platforms, transit to operational areas, conduct decoy, network exploitation, and military deception missions, and then either return to a retrieval platform or scuttle themselves.

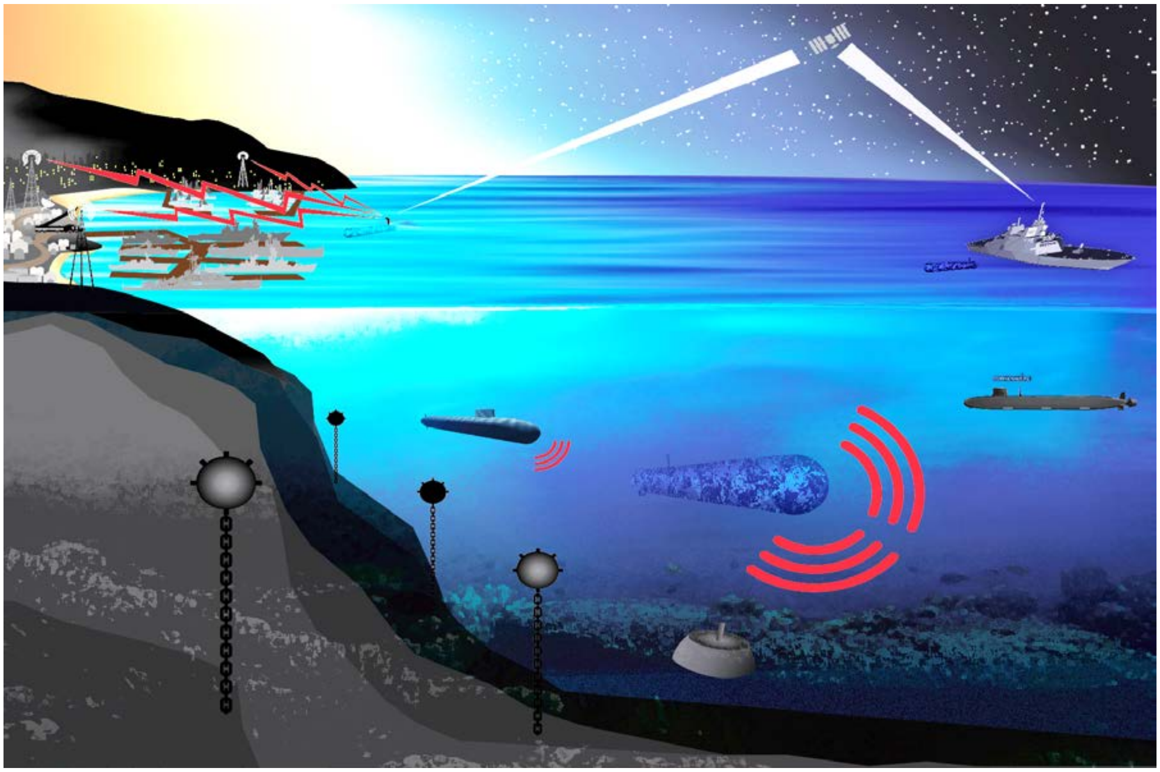


Figure 21. Information Operations CONOPS. UUVs may be designed to complete decoy missions that lure enemy combatants away from high value unit operating areas. UUVs may also be used as MILDEC platforms that are able to broadcast propaganda or project malicious signals into enemy infrastructures.

The first application in the IO domain is to deploy a UUV as an advanced countermeasure. A submarine being tracked acoustically can deploy the UUV, which can then act as a decoy. The UUV emits acoustic signals intended to imitate the host platform and carry out a pre-programmed or adaptively determined route and behavior profile to provide a distraction, allowing the host platform to covertly evade track. Employment of the UUV should result in increased survivability of the high value unit.

Alternatively, a decoy UUV could be deployed to intentionally trigger adversary defenses such as a fixed harbor security system. By preemptively creating a diversion, the UUV can distract defensive resources and reduce the counter-detection risk of a friendly submarine inserting Special Forces or conducting targeted surveillance in other locations.

Another mission profile consists of a deployed UUV impersonating a friendly submarine to infiltrate and probe adversary areas of interest. This disguise could be in the form of acoustic transmissions or a dummy periscope. As an option for non-escalatory

action, a UUV could observe naval operations at close range, and if counter-detected (intentionally or unintentionally) a friendly submarine can observe the adversary reaction from a safer vantage point.

In addition to decoy operations, a UUV offers a unique platform from which to exploit the electromagnetic signal spectrum. A small, unmanned, and nominally expendable vehicle can take greater risk in operating closer to adversary shores than manned high-value units like SSNs. A friendly antenna covertly positioned close to enemy shores offers new opportunities to exploit enemy wireless networks by inserting malicious signals or broadcasting propaganda messages. These transmissions are traditionally considered an unacceptable counter-detection risk for submarines.

These scenarios all present a challenge with respect to recovery of the UUV. If the objective is to attract adversary attention away from the host unit, it is counterproductive for that host to attempt recovery of the decoy. In all of these conditions, the UUV would need to possess a self-destruct or scuttling capability in case of prosecution or capture. Similarly, each mission profile would require significant autonomous performance. Acoustic or RF signaling by a host controlling unit would pose an unnecessary counter-detection risk and negate the advantage offered by a robust decoy vehicle.

The IO mission area requires a vehicle with significant endurance, autonomy, and a robust sensor suite. Large payloads or weapons are not required for this mission area. Vehicles should be as simple and inexpensive as possible, as recovery rates are expected to be low when employed in this capacity.

Chapter Summary

Innovative UUV concepts of operation have been derived over the course of the capstone project. Examples include: Covert Q-route mapping operations for high value unit passage through mined areas, long-endurance decoy and deception operations, and mobile minefield networks. UUVs specifically designed for expendability are also innovative concepts that require significant analysis and will be explored in the following chapters.

In order to identify which UUV characteristics and attributes most heavily influence mission performance and effectiveness, modeling and simulation is used to simulate combat operations in a challenging A2AD environment. Both mathematically-based models and behavioral-based simulation programs are used in the next chapter to investigate the feasibility of all four mission concepts of operation.

VI. UUV CAPABILITY MODELING AND SIMULATION

A. MODELING AND SIMULATION APPROACH

The goal of modeling and simulation is to gain insight on how systems behave prior to real world testing and evaluation. The key advantage of modeling and simulation is that it is relatively easy to vary parameters related to system capabilities and to thereby judge which system capabilities are most important for the particular mission being modeled.

System requirements and capabilities analysis associated with scoped mission areas are accomplished to determine focus areas for modeling and simulation. Results obtained from modeling and simulation are then used to provide significant insights for the analysis of alternatives and proposed future UUV force structure.

System requirements and capabilities are approached from both a functionally-derived perspective and by determining critical operational issues (COIs) in an effort to capture requirements that would have otherwise been overlooked. The requirements analysis located in Appendix D is used to provide an educated baseline of metrics to model to. Derived directly from this requirement analysis, the following measures have been identified as significant factors related to UUV effectiveness:

- Survivability
- Lethality
- Availability
- Sensor Effectiveness
- Host Platform Survivability, Vulnerability and Susceptibility
- Endurance
- Mobility
- Autonomy
- Transportability
- Compatibility
- Interoperability

The analysis tools used included both stochastic, discrete-event simulation, and also deterministic, physics-based models. Diligent effort is placed on ensuring that model and simulation inputs are reasonable and defensible.

B. MANA V OVERVIEW

MANA V is a modeling program developed by the New Zealand Defense Technology Agency. MANA V stands for Map Aware Non-Uniform Automata Vector. The program is a defined as an agent based distillation model. Distillation, as described by the creators of MANA, creates a bottom-up abstraction of a scenario that captures essence of a situation, but avoids non-essential detail. MANA V is based on two key ideas; first is that the behavior of the entities within a combat model, both friend and foe, is a critical component of the analysis of possible outcomes. The second idea is that when human decision making is a key element being modeled, the use of highly detailed, physics-based models for determining force mixes and combat effectiveness may be misplaced analytical effort. (McIntosh, et al. 2007)

SEA-19A chose MANA V as our primary modeling and simulation tool because it is a well-understood, well-documented, and easily used agent-based simulation program. Agent-based simulation programs are particularly useful in modeling that involves critical interactions between multiple platforms or agents. The final and most compelling reason to use MANA V is that it allows for variable behaviors to be modeled within the same entity. Autonomy and behavior profiles play a significant role in unmanned systems and the ability to create and experiment with different behavior profiles improves the modeling of interactions between agents.

MANA V is particularly useful because it incorporates many factors that are critical in combat such as stealth, sensor capabilities, weapon capabilities and communications capabilities. Another high point in the program is that it allows behavior to be modeled according to agent state. This allows for the incorporation of dynamic combat tactics in to what would otherwise be a static model. Combat units are fundamentally individual agents that do not act in totally predictable manners. Environmental and tactical conditions almost always dictate the movement of combat

units and any attempt to model combat in any other manner excludes critical variables related to mission success or failure.

Modeling in MANA V can be complicated. This is a result of the vast number of factors that can be varied in the program. Detailed tracking of changes in variables must occur to prevent unintended variations when comparing separate scenarios. The level of complexity and number of processes that are occurring at each time step also require a significant amount of processing power.

Another significant movement limitation in MANA is the inability for speed to be varied according to a distribution within a single agent state. This complicates modeling efforts, as speed is then required to be varied using multiple different states for the agent. This creates a highly complex model where mistakes can easily be made. Despite the limitations that we encountered using MANA, we found it to be an intriguing simulation program that allowed the project team to model UUV operations in complex ways which appeared to be realistic.

C. BACKGROUND MODELING

Background and foundational modeling is utilized to explore critical topic areas that must be addressed to explore technical requirements associated with current UUVs and future UUV development. The second purpose is to provide realistic physics-based inputs for modeling in MANA V. Subject matter experts, technical documentation, and other model results are used to provide MANA V inputs. The three primary background models produced are: endurance capability, sensor capability, and kinematic engagement.

1. Endurance Capability Model

The endurance capability model is constructed to provide detailed energy storage and consumption characteristics with regard to size and energy capacity vs. velocity. This model provides a solid foundation to examine the capabilities of UUVs with regard to actual power constraints. Configurations examined include a variable diesel engine/lithium-ion hybrid combination and a lithium-ion battery only configuration.

Notional hybrid UUV dimensions for endurance model:

- Shape: Cylindrical
- Length: 22ft
- Diameter: 21in, 48in, 60in
- Fuel, Power, Propulsion Section Length: 10ft
- C3, Weapons, Guidance, Sensor Section Length: 12ft

The configuration of the propulsion section was modeled as an optimization problem using Excel Solver. The objective of the model is to maximize the endurance of the UUV by modifying the kWh available from different combinations of diesel fuel and lithium-ion batteries. The dominating constraint in the model is the amount of "stealth time" required. "Stealth time" relates to how long the UUV must be able to operate on battery only to achieve a given mission.

The assumed lithium-ion battery volumetric energy density of 0.3 kWh per liter is based on a value that is technically feasible and slightly above the range of what is typically employed in current UUV systems from manufacturers such as Bluefin Robotics, Yardney, and Kongsberg Maritime. This value was also confirmed as a reasonable assumption during the Penn State Undersea Technology Short Course in 2012.

The diesel fuel volumetric energy density 2.61 kWh per liter is derived from manufacturer specifications of fuel consumption rates for commercially available marine diesel engines. Manufacturers' fuel consumption figures for generic 7.6 kW and 11.5 kW generators are used. It is apparent that a commercially available diesel engine would require significant modification to function in a small UUV; however the fuel consumption specifications will likely remain in the same range.

The endurance model is designed for maximum flexibility and reconfiguration. Modifiable endurance model parameters and key assumptions include:

- Diesel fuel kWh per liter – The amount of kWh generated per liter of diesel fuel is obtained from commercially available generator ratings, and divided by the fuel burn per hour of operation. Assumed diesel fuel volumetric energy density: 2.61 kWh per liter.
- Lithium-ion battery kWh per liter – The amount of kWh generated per liter of lithium-ion batteries is obtained from commercially available technical specifications of batteries. Assumed lithium-ion volumetric energy density: 0.3 kWh per liter.

- Energy section length and diameter – 10ft length is assumed with variable diameters.
- Energy section hull thickness – A two inch hull thickness is assumed to allow for steel, aluminum, or other materials to be used for hull construction. No analysis on thickness required for specific depths was conducted, but two inches offers a robust thickness.
- Proportion of unusable energy section volume – 30% of total energy section volume is assumed to be unusable. This assumption accounts for hull support structures and required mounting and support equipment that would be required in the energy section. It also allows control surfaces and the propeller installation in the after portion of the hull.
- Diesel generator volume – Volumes from commercially available generators are assumed.
- Electric propulsion motor volume – The electric propulsion motor is assumed to be 0.127 cubic meters. A common figure of 24" x 18" x 18" is assumed. This size will allow for a commercially available 7 kW continuous duty electric motor with a peak power output of 12 kW. Without exact specifications it is difficult to determine a power requirement for the vehicle propulsion. Data from the Penn State ARL Short Course is used to make this assumption.
- Propulsion power consumption – An average propulsion power of 6kW is assumed. This value is based upon propulsion characteristics exhibited by the Penn State University APL LTV38P UUV.
- Hotel load power consumption – An average value of 1 kW is assumed for navigation, system, and mission electronics. This is the power associated with all other power draws other than propulsion.
- Reserve power – 30 kWh of reserve power is assumed. 30 kWh with 20% of that unusable would allow the vehicle to operate for approximately 3 hours in an emergency at full power.
- Unusable battery capacity – An unusable battery capacity of 20% is assumed. Near the full discharge of a lithium-ion battery, the voltage begins to fall and power becomes unreliable.
- "Stealth time" required – This is the amount of time the vehicle must operate on battery only power without snorkeling. This is the primary constraint in the model and is varied to produce the results mix if diesel fuel and batteries are required.
- Battery recharge rate – Optimally, the maximum amount of power will be dedicated to charging the batteries to shorten the battery charging cycle time and minimize the risk of detection. Sufficient power must also be available for continued operations and maneuverability while recharging the battery.

a. Hybrid Diesel-Electric UUV Endurance Analysis

The standard 48 inch diameter UUV configuration is used for the following analysis.

Based on a diesel fuel-only configuration, the total possible operational endurance of the UUV is 864 hours for the 7.4 kW generators and 574 hours for the 11.5 kW generators. As expected the 11.5 kW generators have a larger volume as well as a higher fuel consumption rate than the 7.4 kW model. This diesel-only configuration has all of the total possible operational endurance on the surface or near-surface snorkeling with zero “stealth time” endurance.

Battery only configurations resulted in decreased total possible operational endurance as compared to the diesel fuel only variants. Total possible endurance for a battery only UUV is 63 hours of continuous “stealth time” based on the assumed 0.3 kWh per liter capacity of lithium-ion batteries.

Hybrid configurations result is much greater cumulative “stealth time.” The 11.5 kW generators also provide increased endurance over the 7.4 kW versions, due to the 11.5 kW generators faster recharge rates for the lithium-ion batteries. These faster recharge rates enable the UUV to utilize increased cumulative “stealth time” over the 7.4 kW versions and burn less diesel fuel to complete a full battery recharge. These models indicate that more powerful generators generally are superior to smaller generators.

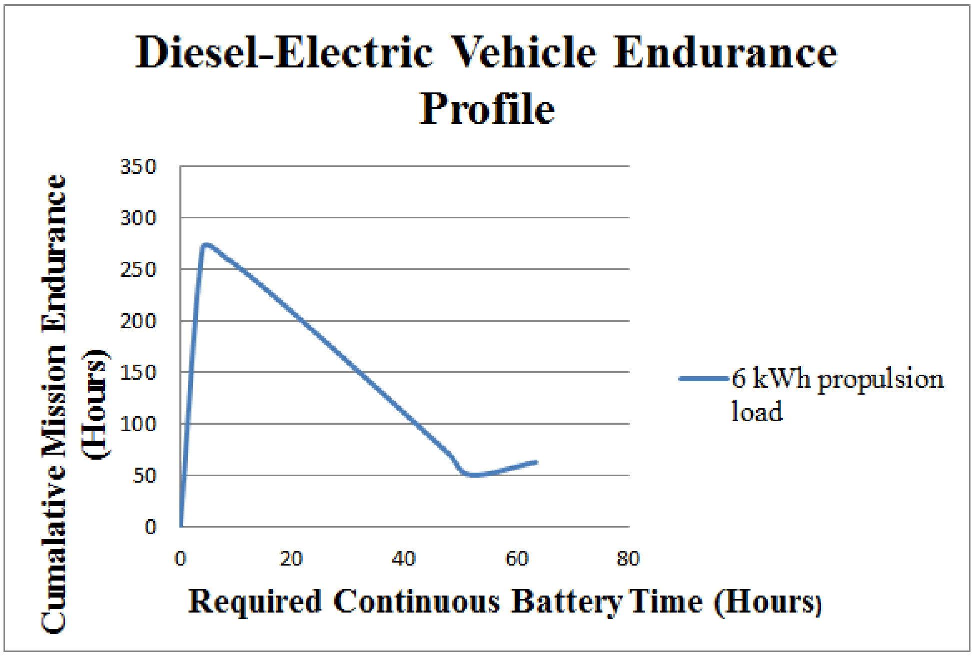


Figure 22. Hybrid Diesel/Electric Endurance Profile. This profile shows a tradeoff profile for diesel fuel and battery cells. UUVs that only need a short duration of stealth battery time can greatly extend amount of total endurance/range by carrying more diesel fuel rather than battery cells. UUVs that need to remain stealthy on battery power for long durations require more battery cells rather than diesel fuel, thereby reducing total mission endurance/range.

UUVs designed with hybrid propulsion plants would likely operate under similar conditions as diesel submarines. This notion necessitates that the majority of the snorkeling time required to run the diesel generators would have to be completed in conditions (such as darkness) that reduce the probability of visual detection by adversaries. Operation in a snorkeling mode does leave the UUV vulnerable to infrared detection, however mission requirements ultimately dictate the required continuous "stealth time," and will also drive the storage ratios between diesel fuel and battery compartments.

b. Battery-Only UUV Endurance Analysis

Most current UUVs are designed with battery only configurations. Sufficient understanding of energy density was obtained by completing the hybrid

analysis. Especially in regards to battery only UUV technologies, it is also important to understand the effect of speed variations on total energy consumption.

Power equations are derived for power draw required, as a function of speed, for a vehicle of given diameter. Performance data provided by Bluefin Robotics was fitted with a third order polynomial to represent the physics of hydrodynamic drag. It can be shown theoretically that propulsion power varies with the cube of vehicle velocity by the following relationship:

$$P = F_d v$$
$$F_d = \frac{1}{2}\rho v^2 A C_d$$

Power is equal to the velocity times the drag force imposed on the body. Drag force is proportional to the density of the fluid, the cross-sectional area of the body, and the square of the velocity.

Therefore, accounting for speed and vehicle size, fitting constants are obtained to represent the drag coefficient and propulsive efficiency. The third order polynomial fits accurately and represents the provided data and consequently provide an acceptable closed form relationship to estimate propulsion power required for a vehicle of defined diameter as a function of vehicle speed. The power equations for these vehicles are:

$$21\text{"}: P = 0.006854v^3 - 0.01917v^2 + 0.01699v - 0.2213$$
$$48\text{"}: P = 0.02003v^3 + 0.1323v^2 - 0.4978v - 0.7488$$
$$60\text{"}: P = 0.03967v^3 + 0.03816v^2 + 0.06117v - 0.1016$$

These power equations were modeled to provide the performance characteristics of maximum UUV range vs. UUV speed as shown in Figure 23. These basic performance characteristics provided inputs for MANA V simulations. Detailed tables for MANA V modeling input purposes are included in Appendix C, Section A.

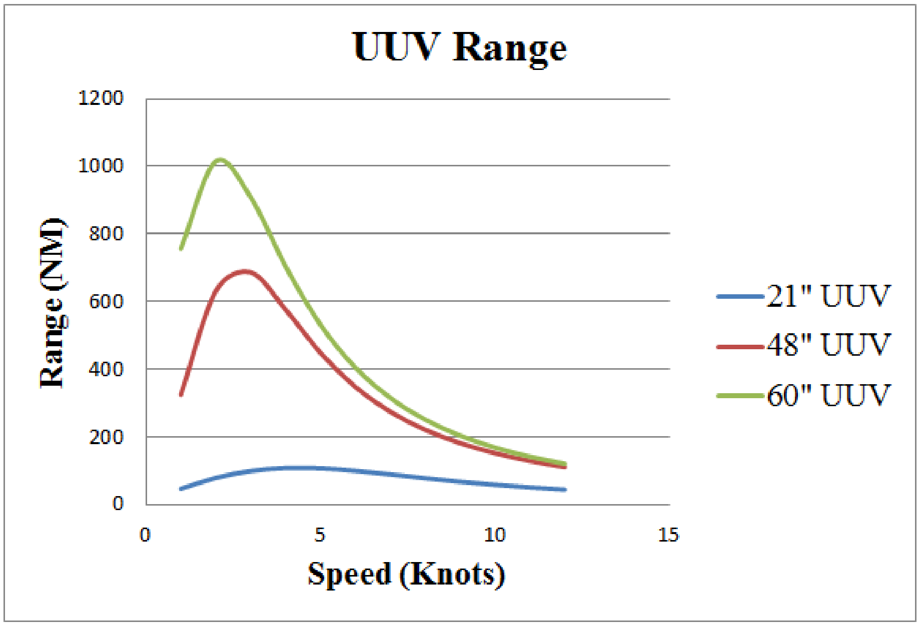


Figure 23. Battery Only UUV Maximum Range vs. UUV Speed — Power Consumption Characteristics. The most efficient speeds are between 2–4 knots for all UUV sizes analyzed. As UUV speed is increased, maximum range is reduced according to the profiles shown.

Figure 23 illustrates that two to four knots is the most efficient speed for UUV operations. The results of the analysis closely resemble the performance specifications and endurance characteristics for current UUVs from various manufacturers. This figure also shows that ranges in excess of 1000 nautical miles are feasible with battery only configurations.

This analysis has shown that battery-only systems have the capability to provide sufficient endurance to field systems with far-reaching military capability. Hybrid systems also may provide significant military capability depending on mission requirements.

2. Sensor Capability Models

a. Acoustic Sensor Capability Model

A passive acoustic sensor model was used to predict acoustic detection ranges of targets. The basic sonar equation and process for range determination is derived from the second edition of the Principles of Naval Weapons Systems (Payne 2010):

$SL - TL - NL + DI \geq DT$

SL = Source Level

TL = Transmission Loss

NL = Noise Level

DI = Directivity Index

DT = Detection Threshold

The greater than or equal to condition is normally written as an equality. It is then understood to mean that if the left hand side's algebraic sum is greater than DT, detection is possible. Rearranging this equation and negating directivity index (DI) we have:

$DT = SL - NL_{ENVIRONMENT} - NL_{SELF\ NOISE} - NL_{SHIPPING} - TL$

The source level of the target vessel is used and the factors of own ship self-noise, environmental noise, and shipping noise are all subtracted from the source level to determine the target detection threshold. Transmission loss is calculated through the equation for total propagation loss (Payne 2010):

$TL = 10\log R + 30 + \square R + A$

TL = Total propagation loss

R = Range

A = Loss due to screening by fixed objects

The total propagation loss equation is used to determine the amount of propagation loss. Detection with certainty is assumed for detection ranges up to one kilometer. Cylindrical spreading is assumed after the first kilometer. The loss due to screening by fixed objects (A) is ignored as an open ocean environment is assumed. Surface ship frequency of interest is assumed to be at 5 KHZ for propagation loss. Submarine frequency of interest with regard to propagation loss is assumed to be 400 HZ.

Using Excel spreadsheet modeling, the maximum range is determined by finding that range resulting in a signal excess of 0 db. To generate usable data for MANA

V simulations, all target noise levels are converted into detection ranges. Each time the simulation is run, a new combination of noise levels is examined to account for variability in ocean environments. Table 4 shows the respective noise levels assumed for the model. These noise level assumptions were collected and based upon data from various Wenz noise curves (Payne 2010), (Urick 1983), and (Powell and Forest 1988).

Noise Level Range Assumptions	
Vessels	**Noise Level Range (dB)**
Enemy Destroyer	105-130
Enemy Submarine	100-120
Active Sonar	200-225
Friendly Submarine	75-85
UUV	75-90
Cooperative Deception UUV	100-110
Environment	50-70
Shipping	55-80
Fishing/Trawling	105-120
Merchant	125-150

Table 4. Acoustic Noise Levels. Decibel levels obtained from Wenz noise curves.

Active sonar ranges are calculated using the same process except the active transmission was utilized for source level. In addition, two-way attenuation of the signal was accounted for with an assumed active sonar transmission frequency of 5 KHZ. This effectively doubles the transmission loss.

Detection ranges for acoustic sensors deployed from aircraft were treated in a different manner. It is assumed that maritime patrol aircraft (MPA) and helicopters will utilize sonobuoys to attempt to localize UUVs and submarines. It is assumed that a pattern of sonobuoys will be laid following initial detection by a cueing platform. It is also assumed that the aircraft is vectored to within a ten nautical mile radius of the submarine or UUV location. From this point, the sonobuoy is treated as a cookie-cutter sensor with a set detection radius of 1,000 meters. The highest probability of detection assumed with vectoring of the aircraft is 8%. At the lowest detection probability of 1%, the cookie-cutter assumption is made that the MPA can hold one sonobuoy for each of the 100 square nautical miles in the simulation, and the MPA is searching without cueing.

With all required input data collected, 10,000 simulation runs are conducted for each sensor and target pair. It is important to note that this particular model only deals with direct path propagation in the ocean. Bottom bounce and convergence zones are not examined in this model due to assumed limitations of UUV sonar and the associated processing capability required. Descriptive statistics and a histogram are created for each target/sensor pair and detection probability tables are generated. These detection probability tables located in Appendix C, Section B are then used to generate the acoustic sensor detection profiles in MANA V.

b. Radar and Electronic Support Measures (ESM) Models

Detection with radar sensors is governed by the radar range equation (Payne 2010):

$$R = \sqrt{17}\left(\sqrt{h_{transmitter}} + \sqrt{h_{target}}\right),$$

where range (R) is in kilometers and height (h) in meters. The heights utilized in the modeling are shown in Table 5. Calculations for electronic support measures are estimated by adding 50% to the radar range to model atmospheric ducting.

Radar Range Inputs	
Unit	**Sensor Height (Meters)**
Enemy Surface	15
Enemy Land Based Radar	50
Friendly Submarine	3
UUV	1

Table 5. Radar Sensor Heights

Helicopter and maritime patrol aircraft pilots were consulted to determine approximate airborne radar detection range probabilities. These probabilities are also applied to land-based radar ranges. Corrections are made for increased sea state conditions and operator ability to discern the target periscope from background clutter. Land-based radars were assumed to be capable conventional radars and airborne radars

are assumed to be highly capable inverse synthetic aperture radars. The result is a very demanding environment for UUVs and submarines to operate with an exposed mast, especially close to shore. Radar and ESM detection probability tables are also located in Appendix C, Section B. These detection probability tables are then used to generate the radar and ESM sensor detection profiles in MANA V.

c. Kinematic Engagement Model

The probability of kill associated with each weapon is estimated based upon an Excel simulation that accounts for variation in engagement geometry, vehicle kinematics, countermeasures and weapon reliability. The weapons that are modeled are Mk-46 and Mk-48 torpedo-equivalent weapons. These two weapons are modeled for both friendly and enemy units. The Mk-46 equivalent specifications are an 11,000 meter range with a velocity of 20 meters/second (Jane's 2005). The Mk-48 equivalent specifications are a 38,000 meter range with a velocity of 28 meters/second (Jane's 2005). Weapon reliability for all weapons is assumed to be 90%. Weapon susceptibility to countermeasures is assumed to be 33% for weapons fired at manned platforms and 15% for weapons fired at UUVs. UUVs are assumed to have a more limited evasion and countermeasure capability than manned platforms. Initial detection velocity and torpedo evasion velocity assumptions for various platforms are detailed in Table 6.

Kinematic Engagement Model Velocity Inputs		
Unit	**Initial Velocity (Knots)**	**Evasion Velocity (Knots)**
UUV	5	5
Friendly Submarine	8	25
Enemy Submarine	8	18
Enemy Surface	12	30
Merchant Vessel	18	18

Table 6. Kinematic Engagement Velocity Inputs. Initial velocities are the assumed standard operational speeds. Evasion velocities are the assumed maximum speed of each platform. UUV and merchant vessels are assumed to not have the capability to detect that they are being targeted, and therefore do not employ evasion tactics.

For each unique target, that target velocity and the weapon velocity are used to determine minimum and maximum closure rates. The maximum closure rate

occurs when the weapon and target are on opposite, head-on collision courses. The minimum closure rate occurs when the weapon and target are on the same course. The minimum and maximum values are then utilized to generate a random closure rate between these values for simulation purposes.

The next step in the process is to examine how far the weapon can close the target before the target can effectively evade at maximum speed. This is the delay time to maximum evasion course and speed. Two factors are considered, attack recognition time and time required for evasive action.

Attack recognition is defined as the time required for the attacked unit to recognize that there is a torpedo in the water, conduct counter-fire, and then order an evasion course and speed. This time is assumed to be normally distributed with a mean of 45 seconds and a standard deviation of 10 seconds.

The evasive action time is defined as the time that is required to turn the ship to an evasion course and increase to maximum speed and is assumed to be uniformly distributed between 0 and 90 seconds. These values were chosen because the target vessel is between 0 and 180 degrees from the optimum evasion course and a 2 degree per second turn rate is assumed for all vessels. The assumed tactic in this simulation is that the target vessel recognizes it has been shot at, returns fire and then turns to the opposite course as weapon bearing and opens the range at maximum speed.

Attack recognition delay and evasion delay are summed to determine the total delay. Total delay time is then multiplied by the weapon speed to determine the range the weapon closes before the target begins to open the range. Total delay time is then subtracted from total weapon run time to determine the amount of available run time left on the weapon. Closure rate is then recalculated for the new weapon and target geometry and kinematics. This new closure rate is multiplied by the remaining weapon run time to determine if sufficient closure is possible for a potential kill.

This simulation is run 10,000 times to generate a probability of kill for a given range. The simulation is iterated in increasing 1000 yard increments until a probability of kill of zero is achieved. Probability of kill is then multiplied by the assumed reliability of the weapon and susceptibility to countermeasures. Targets that

have no detection capability against a torpedo can also be modeled by negating attack recognition and evasive action times.

Probability of kill assessments for the various platforms and ranges are included in Appendix C, Section C. These probability tables are then used to generate weapon effectiveness parameters in MANA V.

D. MANA V MODEL VALIDATION

Prior to full scale utilization and modeling with MANA V the project team validated the motion engine in MANA V to ensure that the background inputs and processes occurring in the program do in fact represent reality. To conduct this validation a distilled motion model was produced. This model utilized an enemy submarine and UUV which are randomly placed on a twenty five by twenty five nautical mile map. The enemy submarine and the UUV search for each other at eight knots and four knots respectively. Each has an average path length of 10,000 meters. The time to first detection is the output of this model. The model was replicated 1000 times and the results were compared to the value that is expected from the random search with dynamic enhancement equation.

To validate the MANA model, it was compared to the random search model for area search. The random search model predicts that the probability of detection by time *t* is as follows (Washburn and Kress 2009):

$$P_D(t) = 1 - e^{\frac{-WVt}{A}}$$

where,

$P_D(t)$ = probability detection as a function of time

W = searcher sweep width (twice the detection range)

V = searcher speed

t = time

A = search area

Additionally, this model also utilized a searcher dynamic enhancement speed to allow the random search model to accommodate both a moving searcher and target. The dynamically enhanced speed ($\tilde{V}$) is approximately the mean relative speed between the searcher and target. The dynamic enhancement speed relationship is as follows (Eagle 2011):

$$\tilde{V} = \frac{1}{2}\left[\max(U,V) + \sqrt{U^2 + V^2}\right]$$

where,

$\tilde{V}$ = searcher dynamic enhancement speed

V = searcher speed

U = target speed

An important assumption in this area search model is that the searcher has a cookie-cutter sensor, and the searcher's sweep width is then twice that of its sensor's detection range. In a perfect scenario, a searcher would search an area continuously and have no overlap and cover all of the search area. In reality, searches will have overlap, either due to the necessity to turn, imperfect navigation, environmental uncertainties, or target motion. Figure 24 shows probability of detection by time *t* from the MANA V simulation and from the random search model. The results match well, and support the validity of the MANA V simulation.

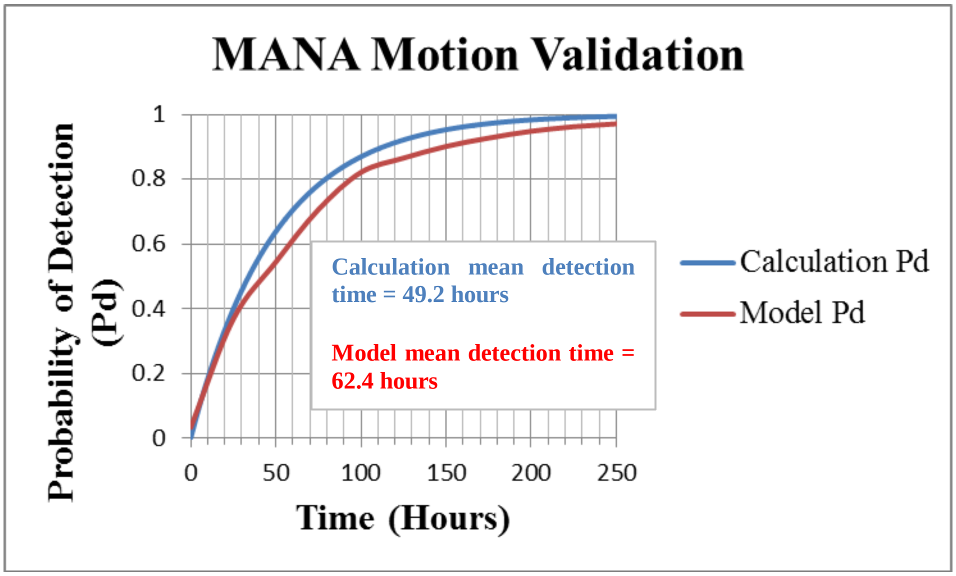


Figure 24. MANA V Motion Validation. The similar curves show that MANA V probability of detection models closely match the accepted mathematical models used for validation.

E. MISSION MODELING

1. Design of Experiments

The base MANA V model is designed to simulate 100 NM by 100 NM A2AD environments where the enemy exhibits control of the sea, air, and the electromagnetic spectrum. A visual snapshot of the MANA V model is shown in Figure 25.

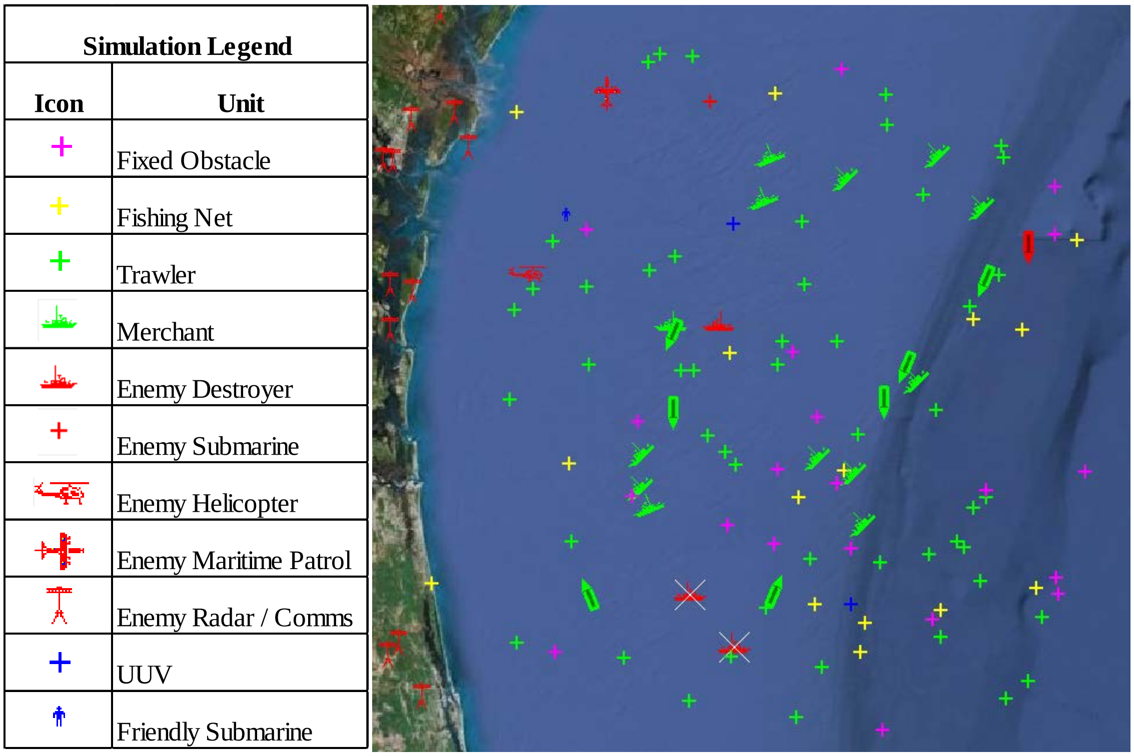


Figure 25. MANA V Simulation Screenshot and Legend

Figure 25 also illustrates a challenging high contact density environment. Aside from the high contact density, the enemies possess a robust communications capability. Enemy units have real-time tactical data links between multiple platforms such as enemy surface combatants, submarines, aircraft, and land based sensors. This allows for the use of real world tactics where the surface combatants vector maritime patrol aircraft to prosecute sub-surface contacts. Enemy aircraft conduct cyclic operations to simulate realistic enemy air cover in the A2AD environment. Adversary surface combatants and submarine initial starting positions are randomly generated and motion follows random search with average path lengths of 10,000 meters. The mission of the enemy units is to find and kill friendly submarines and UUVs in the operating area.

All players are assigned behavioral traits to account for unit level tactical decision making. Appendix C, Section D details the specific behaviors that are programmed into both the friendly and adversary mission platforms within the MANA V model.

All scoped missions, with the exception of mine countermeasures, utilized a full factorial design method. The mine countermeasure mission area negated maritime traffic

and was executed in a smaller area to simulate a heavily mined, geographically constrained navigational area such as a chokepoint.

Variable simulation factors include contact density, employment of enhanced UUV avoidance, and vehicle size. Significant factors and factor levels are listed in Table 7.

Factor	Factor Levels	Description
UUV Size	21"	Torpedo tube launched vehicle.
	48"	Notional ULRM launched vehicle.
	60"	Notional LCS launched vehicle.
UUV Manuevering	Constant Speed	Constant 4 knots regardless of contacts.
	Variable Speed	8 knot avoidance of contacts for 6 minutes.
Contact Density	High	4 Enemy surface combatants
		1 Enemy submarine
		20 Merchants
		50 Trawlers
		15 Nets
		20 Fixed Obstacles
	Low	2 Enemy surface combatants
		1 Enemy submarine
		10 Merchants
		25 Trawlers
		5 Nets
		10 Fixed Obstacles
Submarine Involvement	Yes	Submarine conducts independent mission.
	No	Submarine not in simulation.

Table 7. MANA V Variable Factors. The model factors and factor levels show the different variations that are investigated to evaluate UUV measures of performance and effectiveness.

2. Intelligence, Surveillance, and Reconnaissance (ISR)

The United States Navy is committed to developing a fleet of large diameter UUVs (LDUUVs) to be operational within the next decade. LDUUVs concepts may have a distinct advantage over smaller sized UUVs for ISR missions due to increased endurance and sensor capacity. Several missions call for persistent ISR coverage and a long endurance vehicle seems to be an appropriate tool for completing these mission requirements. Although the Navy is moving forward with the LDUUV program, its true operational capabilities and value added to the naval force are yet to be determined.

Until sufficient test and evaluation data for current developmental LDUUV programs of record becomes available, it is useful to conduct analysis on other factors that may affect ISR UUV performance and mission success. In particular, the goal of the SEA-19A ISR analysis is to identify critical operating issues with missions conducted in heavily contested A2AD wartime environments. Critical analysis of the ISR mission area identified three areas of interest to explore:

1. Number of UUVs used per sortie
2. Recoverable versus expendable UUVs
3. Avoidance programming versus non-avoidance programming

These three factors were chosen because the results of the analyses can be extended to other possible performance factors such as number of contacts sensed, maximum operating ranges, and vehicle size.

a. ISR Mission Success Based on Number of UUVs Deployed per Sortie

SEA-19A desires to explore how deploying greater numbers of UUVs can impact overall mission success. The scenario consisted of UUVs departing a launch platform and transiting to an operational area. Upon reaching the coast, UUVs conduct mobile ISR missions along a 90 nautical mile shoreline and then return to the vicinity of the original launch location for recovery. The mission is considered successful if a single UUV returns to the launch platform regardless of the number deployed. The model was run by varying initial launch distance from shore and by varying number of UUVs deployed per sortie. For sorties with more than one UUV, the number of UUVs were split equally and sent along the same path but in reciprocal patterns as shown in Figure 26 (i.e., one set of UUVs traveled counter-clockwise while the other set of UUVs traveled clockwise).

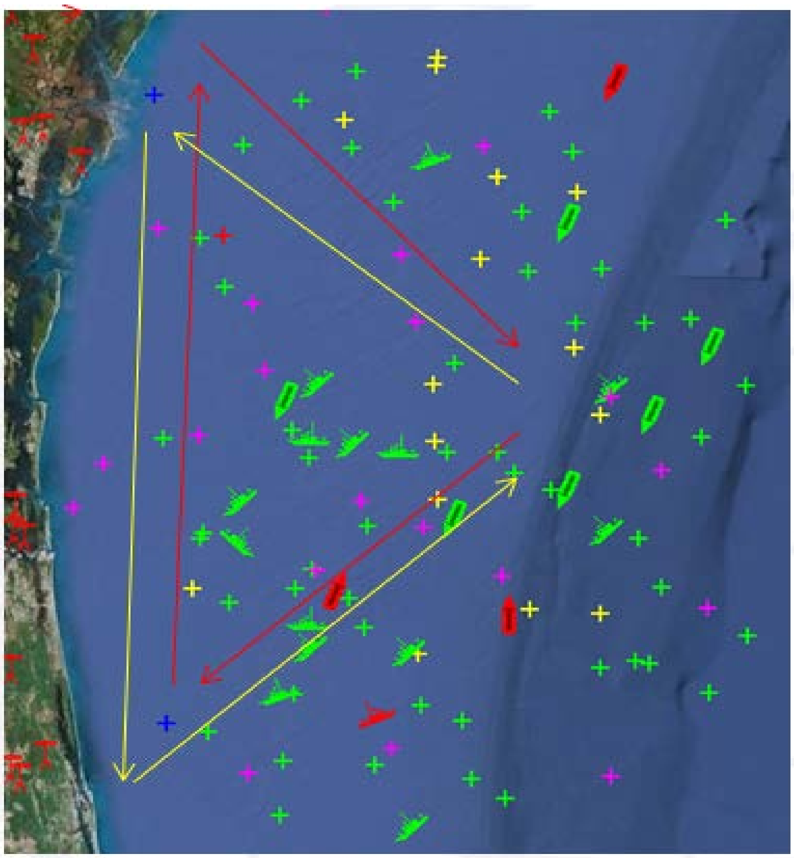


Figure 26. ISR UUV MANA V Mission Profile. UUVs are launched and transit to coastline. Upon arrival, UUVs conduct ISR operations along the 90 NM coastline. If required, the UUV then transits back to a recovery area. If more than one UUV is utilized, the vehicles travel in reciprocal patterns as shown by the yellow and red tracks.

Initial launch distances were varied between 12–65 nautical miles and the number of UUVs deployed per sortie varied between 1–8 UUVs. Figure 27 shows the results of the analysis.

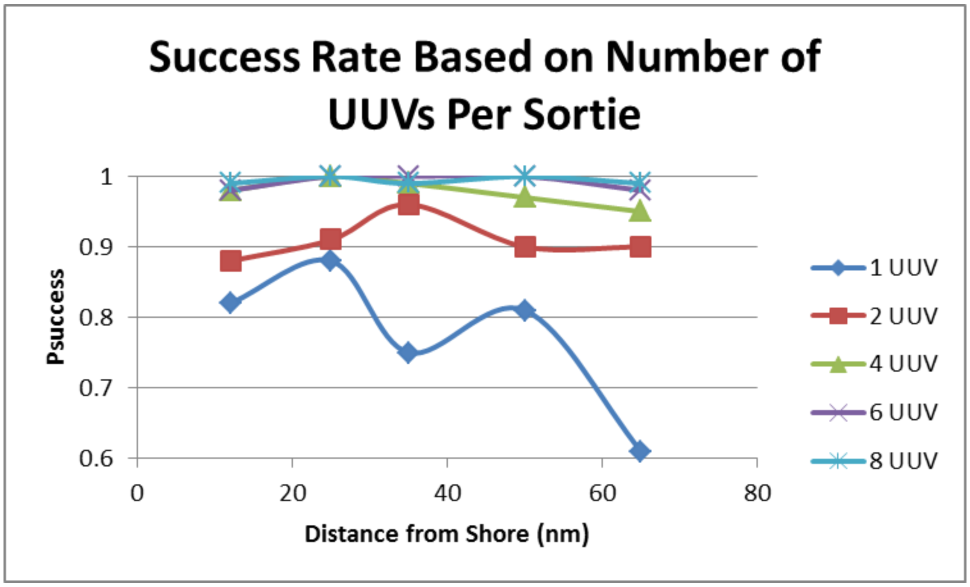


Figure 27. ISR Mission Success Based on UUV Sortie Size. As the numbers of UUVs deployed are increased, the probability of mission success also increases. The most significant increase occurs between 1 and 2 UUV configurations. The law of diminishing returns also begins to apply after the deployment of 4 UUVs.

The results are predictable, in that as greater numbers of UUVs are deployed, the probability of mission success increases. Although predictable there is useful analytical information that can be drawn from the data. First, the most dramatic change in mission success rates by proportion occur between the 1 UUV and the 2 UUV sortie sizes, with the disparity in success rate between these two groups expanding as the launch distance from shore is increased. 2 UUV sorties result in a 9% increase in mission success rate between the two groups at 50 NM and surges to 29% increase at 65 NM. This trend of expanding differential success rates between groups as launch distance increases can be applied to all sortie sizes. As a result, increased numbers of UUVs deployed should be considered as launch distances increase.

The second important thing to draw from the data is that variation in mission success rates decreases as the number of UUVs increases over the range of distances. For example, looking at the 1 UUV sortie size the variation in success rate between 12 NM and 65 NM is 21%. Over the same range of launch distances, the variation in the 8 UUV sortie is only 1%.

Data also reveals that the law of diminishing returns takes hold relatively quickly to the extent that there really is no statistical difference between using 6 UUV and 8 UUV sorties. Even the 4 UUV sortie has very little statistical difference when compared to the 8 UUV option. This type of analysis is especially useful when conducting an analysis of alternatives and determining future UUV procurement quantities.

To summarize, the factors that may need to be considered when deciding on number of UUVs to use for an ISR mission in a highly contested A2AD environment include, but are not limited to:

- 2 UUV vs. 1 UUV sorties result in significantly increased mission accomplishment
- Greater distances traveled result in increased disparity between UUV mission success rates over the range of sortie sizes
- Variation in success rate decreases with increased numbers of UUVs over the range of distances traveled
- Law of diminishing returns takes hold as UUV sortie size is increased

Revisiting the concept of the LDUUV program, in order to maintain a small UUV fleet size (approx. 10 LDUUVs), it seems that the vehicle currently being built will need to be quite robust and have an extremely low probability of detection to survive a heavily contested A2AD environment. Like many other high technology concepts, costs of the LDUUV program are beginning to soar, and as of right now there are no intentions of purchasing large quantities. Based on cost alone, the potential loss of an LDUUV may not satisfy expected returns on investment. Overall, the analysis presented indicates that greater numbers of UUVs provide much better success rates up to a point at which the law of diminishing returns takes precedence. Continued tradeoff analysis needs to occur prior to going all-in on the LDUUV program. For example, imagine that you could purchase eight less capable UUVs for the price of one LDUUV. Not only can mission success possibly increase, but the cost of losing one or more of the UUVs would be far less.

b. Expendable vs. Recoverable ISR UUVs

Much of modern thinking and research in regards to UUV employment is centered on the need to design for recoverability. This is a sound approach when UUV costs are so high that loss of the UUV asset would place undue strain on future operations. Our project team seeks to challenge this line of thinking and provide some insight into the possibilities of designing UUVs explicitly for expendability. The expendable ISR UUV model scenario is designed just like the scenario used for the ISR mission success based on number of UUVs deployed per sortie in the previous section. The only difference being that instead of returning to the launch platform at the end of the ISR mission, the UUV surfaces and transmits the recorded data then self-destructs or scuttles itself. Figure 28 shows the data for a 1 UUV comparison.

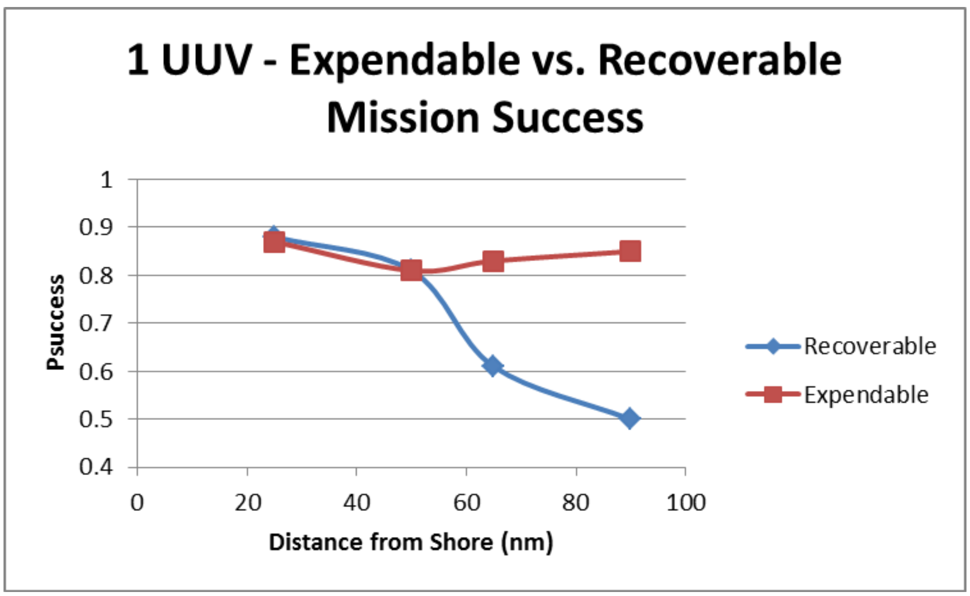


Figure 28. One ISR UUV Expendable vs. Recoverable. As the launch and recovery distance is increased, UUVs that are designed for expendability are able to exhibit higher mission success due to not having to make a return trip to the recovery area through the A2AD environment.

Looking at the 1 UUV comparison there are a few things to note. It indicates that at shorter launch distances there is a negligible difference between recoverable and expendable mission success rates. However, as launch distance increases, expendable UUV success rates remain relatively static while recoverable UUV

success rates decrease. This is a result of the removal of the requirement for the UUV to return to the launch platform, hence less distance traveled in an A2AD environment. Further analysis was conducted to see whether the results of the 1 UUV model hold for increased numbers of UUVs. Figure 29 shows the results of the 2 UUV comparisons between expendable and recoverable UUVs.

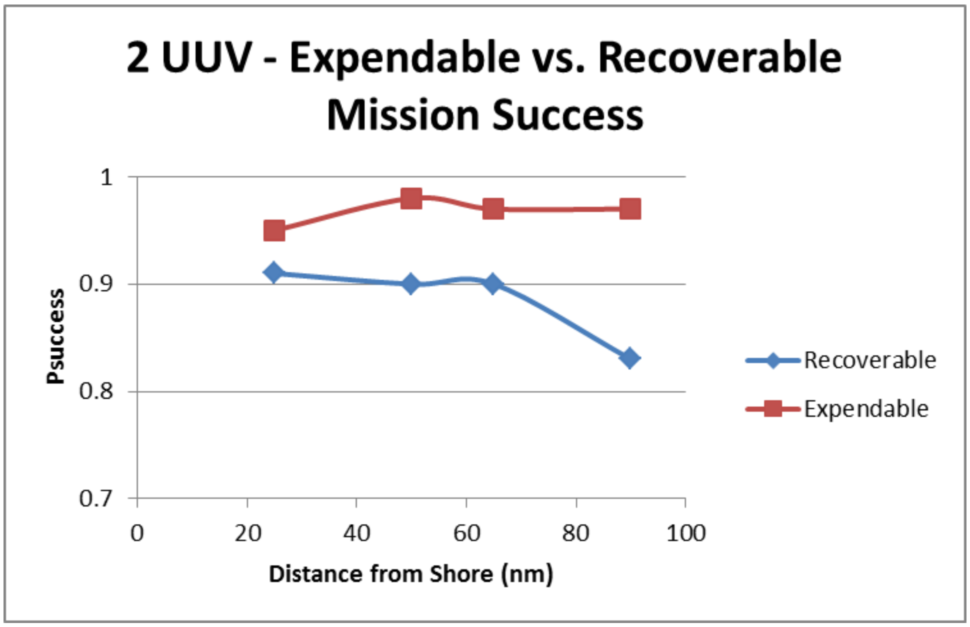


Figure 29. Two ISR UUV Expendable vs. Recoverable. Results of the 2 UUV configurations are similar to the 1 UUV configurations in Figure 29. UUVs that are designed for expendability are able to exhibit higher mission success due to not having to make a return trip to the recovery area through the A2AD environment.

As seen from the results in the 2 UUV case, the mission success rate also remains relatively stable over all distances for the expendable variant. Like the 1 UUV case, there exists divergence in mission success for the recoverable variant, further supporting the use of expendable UUVs over recoverable UUVs.

It is also useful to see how expendable UUVs of smaller sortie sizes compared to recoverable UUVs of a greater sortie sizes. Figure 30 shows the results of this analysis.

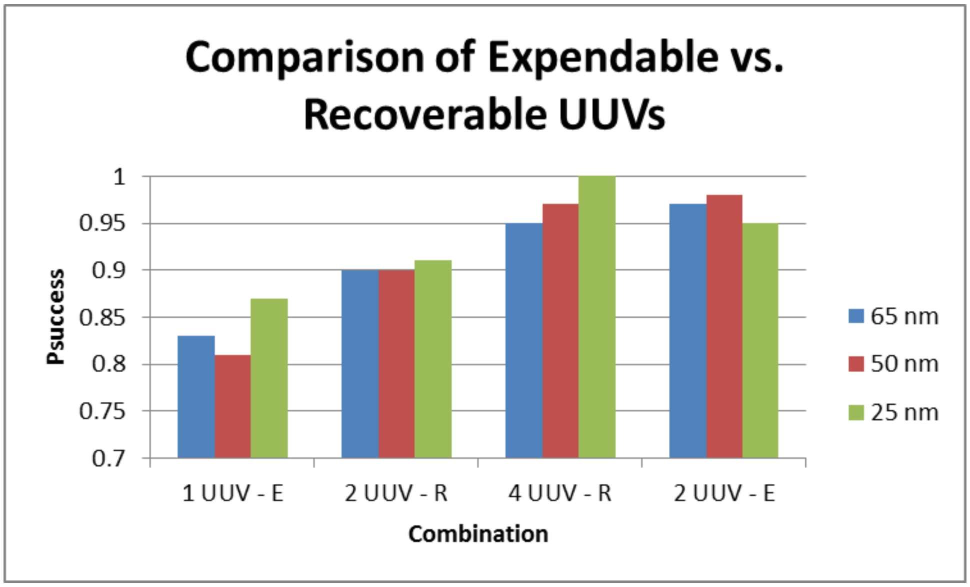


Figure 30. Consolidated ISR UUV Expendable vs. Recoverable. Results show that similar probabilities of mission success can occur with an expendable sortie that is approximately half the size of a recoverable sortie.

The comparisons show that mission success rates are statistically similar by using expendable UUV sorties that are half the size of a recoverable UUV sorties. For example, the 2 UUV expendable sorties success rates are statistically similar to those of the 4 UUV recoverable sorties, yielding greater than 95% mission success over the launch distances shown. These results support the notion of using expendable UUVs over recoverable UUVs due to the ability to achieve similar mission success probabilities with fewer UUVs.

The future UUV force structure may incorporate both concepts. Decisions between recoverable and expendable depend most heavily on cost vs. benefit ratios and returns on investment. Unfortunately much of the costs associated with recovery will become sunk costs. Also much of the financial risk is tied with the fact that there is not sufficient real world data available to determine UUV survivability in A2AD environments.

c. ISR UUV Avoidance vs. Non-Avoidance Programming

With enemy combatants, mines, fishing nets, trawlers, commercial shipping, and natural barriers, UUV obstacle avoidance has become a critical

consideration for UUV design. This analysis explores whether avoidance programming (speed and maneuver) yields sufficient difference in mission success rates to justify utilizing it. This is an important analysis due to the fact that significant alterations in both speed and maneuver have a definite impact on UUV endurance. Figure 31 shows a comparison between using avoidance programming and not using avoidance programming for both 1 and 2 UUV sortie sizes.

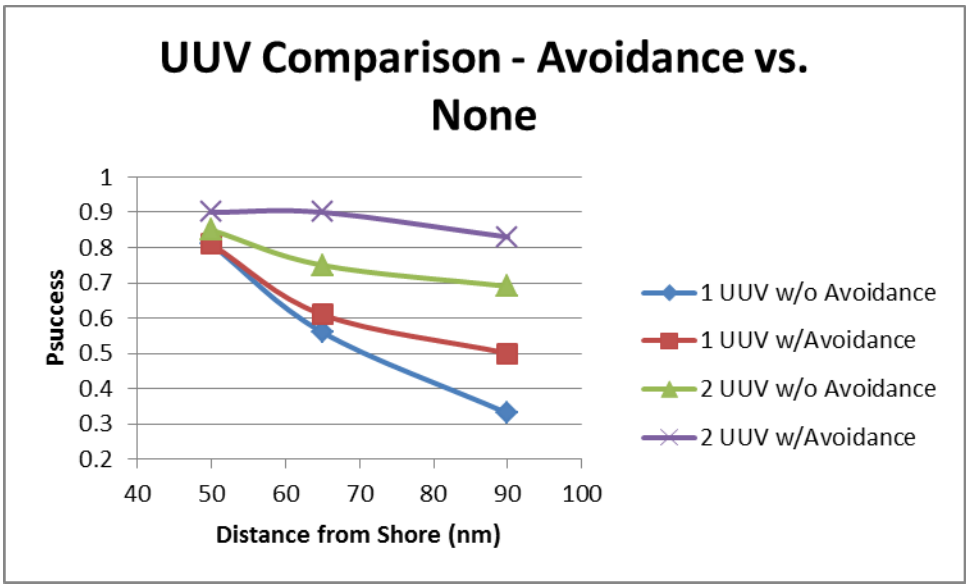


Figure 31. ISR UUV Avoidance vs. Non-Avoidance. Results show that UUVs that incorporate significant obstacle avoidance hardware and programming are able to achieve higher probabilities of mission success.

From the data it is easy to see that as launch distance increases the use of avoidance programming also increases mission probability of success. Although percentages of all four combinations are greater than 80% at the 50 NM for the designed scenario, as launch distance increases there is divergence between the avoidance and non-avoidance sets. For example, at 50 NM both 1 UUV scenarios have an 81% mission success rates, but as distance from shore increases the 1 UUV without avoidance programming success drops to 33% whereas the 1 UUV with avoidance programming success still maintains a 50% success rate (i.e., the difference grows from 0% to 17% over that range). A similar trend is also seen in the 2 UUV cases. Based off these findings

the merit of using avoidance programming is definitely justified and recommended, but must be factored into UUV range and endurance calculations.

Although not captured directly from the data but recognized during scenario testing, avoidance maneuvers reduce the overall linear distance that can be traveled by the UUV. Linear distance will remain the same given a constant speed but since the path of the UUV is not a straight line, but rather a series of obstacle avoidance maneuvers in route to its intended destination, it travels a much further distance over the same linear displacement. As stated, this data was not a direct output of the model but was derived because the fuel endurance values had to be increased at 90 NM for the avoidance programmed UUV because it never made it back to the recovery vehicle due to fuel exhaustion. In the case of the non-avoidance programmed UUV the vehicle did not suffer a single fuel exhaustion casualty at the 90 NM distance.

Overall the data suggests that the increase in mission success rate with avoidance programming justifies designing UUVs with avoidance programming. With the increase in mission success rate comes the trade-off of having a lower linear displacement of travel. Because of this, consideration must be made to designed launch distances if avoidance programming is utilized.

d. Key ISR Modeling Takeaways

Based on the three analysis factors of UUV sortie size, expendable versus recoverable UUVs, and avoidance programmed versus non-avoidance programmed UUVs resulted in the following key notions:

- At least 2 or more UUVs should be utilized when high mission success probabilities are required
- Multiple UUVs deployed at once yield better mission success rates to a point where the law of diminishing returns sets in
- Use of expendable UUVs may result in greater probability of mission success over use of recoverable UUVs
- Avoidance programming results in significantly greater probability of mission success over use of non-avoidance programming, but decreases overall max range

3. Information Operations (IO)

Information Operations is a broad discipline with a wide variety of necessary skill-sets and capabilities. Particularly significant for the employment of UUVs, the areas of military deception and intelligence are elements of a notional IO cell (Scaparrotti 2013). This analysis will address the effectiveness of UUVs deployed in this capacity.

This mission area is envisioned with two distinct scenarios. The first subset of deception operations addresses employment against enemy naval exercises or operations in the open ocean environment. In this assessment and observation scenario, an SSN deploys a decoy UUV which proceeds into the enemy exercise area. Traditionally, SSNs will observe enemy exercises from a safe distance, gathering any available intelligence while minimizing risk of counter-detection.

The second scenario of the military deception mission area consists of a SSN which must travel close to adversary shores and defenses to conduct a sensitive mission, such as SOF insertion/extraction or a specified high-priority intelligence collection. In this distraction scenario, a decoy UUV is deployed to confuse defensive resources and mitigate the risk of counter-detection or prosecution to the SSN.

a. IO UUV Assessment and Observation Model

There are different options on how to employ a decoy UUV in this capacity. One option is to deploy the UUV with a covert profile for the purpose of assessing the enemy ASW capability. In this posture, the UUV might be configured to display a profile approximately representing that of a friendly submarine. This profile could include acoustic characteristics as well as mast exposure. The UUV and standoff SSN assesses the response of the enemy force.

Another option for deployment is for the UUV to present an overt profile, intentionally louder than friendly submarines and possibly with more constant mast exposure. This posture is employed with the intention of observing the enemy response upon detection of an unanticipated submerged contact. In both cases the UUV acts as a risk mitigation tool for the friendly SSN, permitting operations in closer proximity to adversary forces.

To analyze this concept, a range of possible enemy responses must be considered along with an appraisal of the likelihood that each of the responses would be used. These factors comprise a mixed strategy. The scenario is similar to a two person matrix game, with the SSN selecting a deployment posture for the UUV and the enemy force selecting a response upon detection. A failure to detect is also accounted for, though not part of the matrix game. The assumed possible responses are:

- Actively prosecute the contact using all available ASW resources. In a peacetime scenario, this would result in overt tracking. A combat scenario could include weapons employment.
- Halt the exercise or operation and vacate the area, evading the perceived contact.
- Show no overt response but observe the contact, effectively collecting counter-intelligence.

The matrix depicted as Table 8 shows nominal "payoffs" resulting from each of these scenarios, as envisioned for the initial encounter. The payoff numbers are not specifically derived from any driving factor. The numbers are only conceived in a "better, good, neutral, bad, worse" (+2 to -2) formulation. Note that while this is laid out similar to a two-person zero-sum game, this is a game of imperfect information. Each side does not know which choice the other side has made, and therefore does not know the payoff resulting from his choice. There is also a column representing the payoff associated with Red's failure to detect the UUV, although this is not a strictly an available "choice" and therefore not typically included in a matrix game formulation. It can also be seen that there is a saddle point to the game where Blue deploys in overt posture, and Red reacts with observe.

Blue / Red	Prosecute	Cease Ops	Observe		No Detection
Covert	1 / 1	-1 / 1	-2 / 2		1 / 0
Overt	2 / -2	1 / 0	-1 / 1		2 / -2

Table 8. IO Assessment and Observation Initial Payoff Matrix. This matrix shows the nominal payoff for Blue and Red forces as envisioned for the first engagement with a decoy UUV.

In order to capture the reality that this game is not played only once, but many times, expressions are generated to describe the change in payoff for each result as a function of the number of engagements. Number of engagements is used as an example of an independent variable controlling the change in payoff, but a specific time step or other temporal factor could also be derived. For a series of 20 engagements, the expressions in Figures 32 and 33 illustrate the payoff of each possible result. Blue payoff, p, and red payoff, q, are functions of the number of engagements, x.

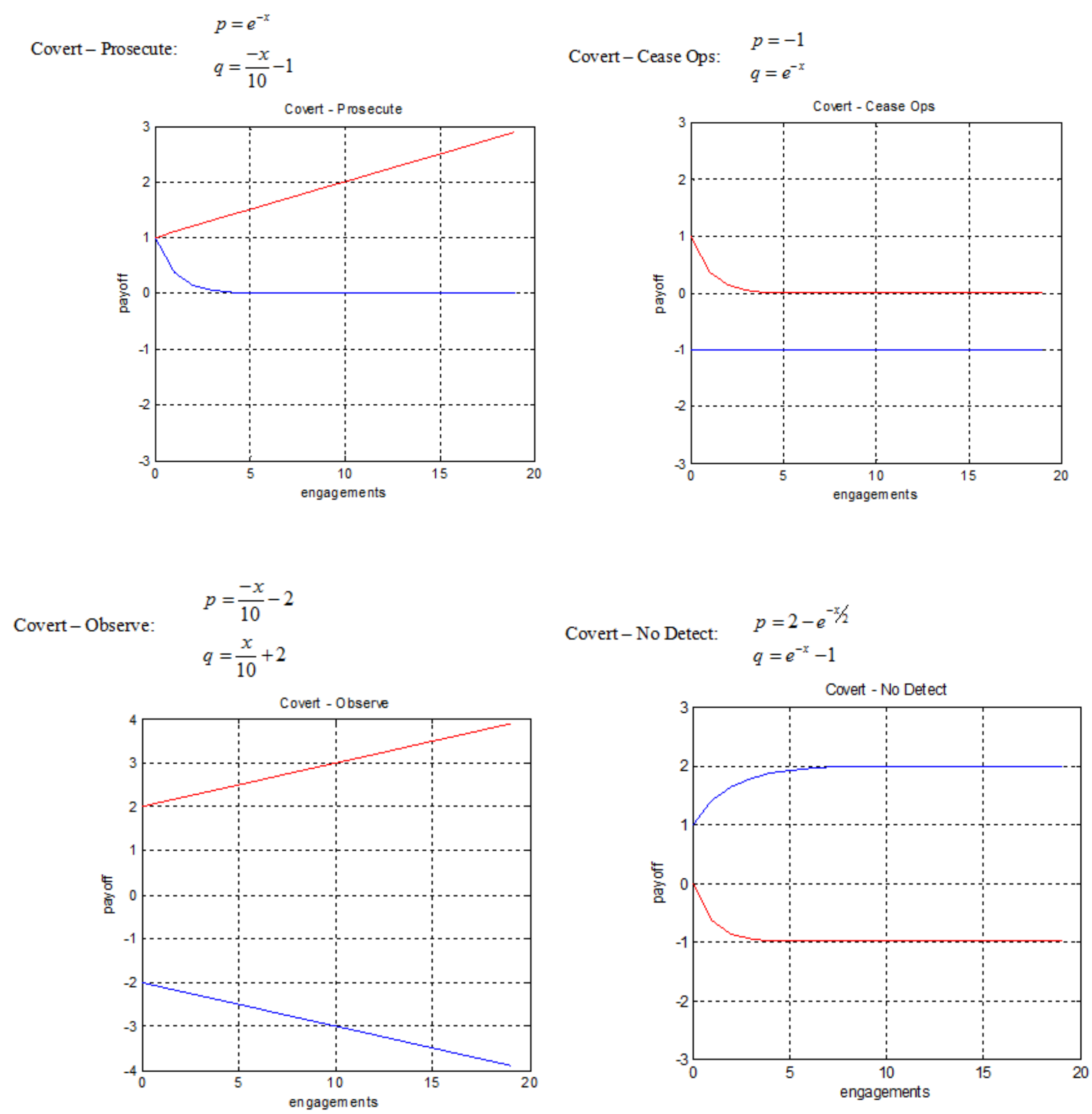


Figure 32. IO Assessment and Observation Payoff Relationships. The expressions and plots describe the change in Blue and Red payoffs over the course of multiple engagements, or over the course of time of employment of the decoy strategy.

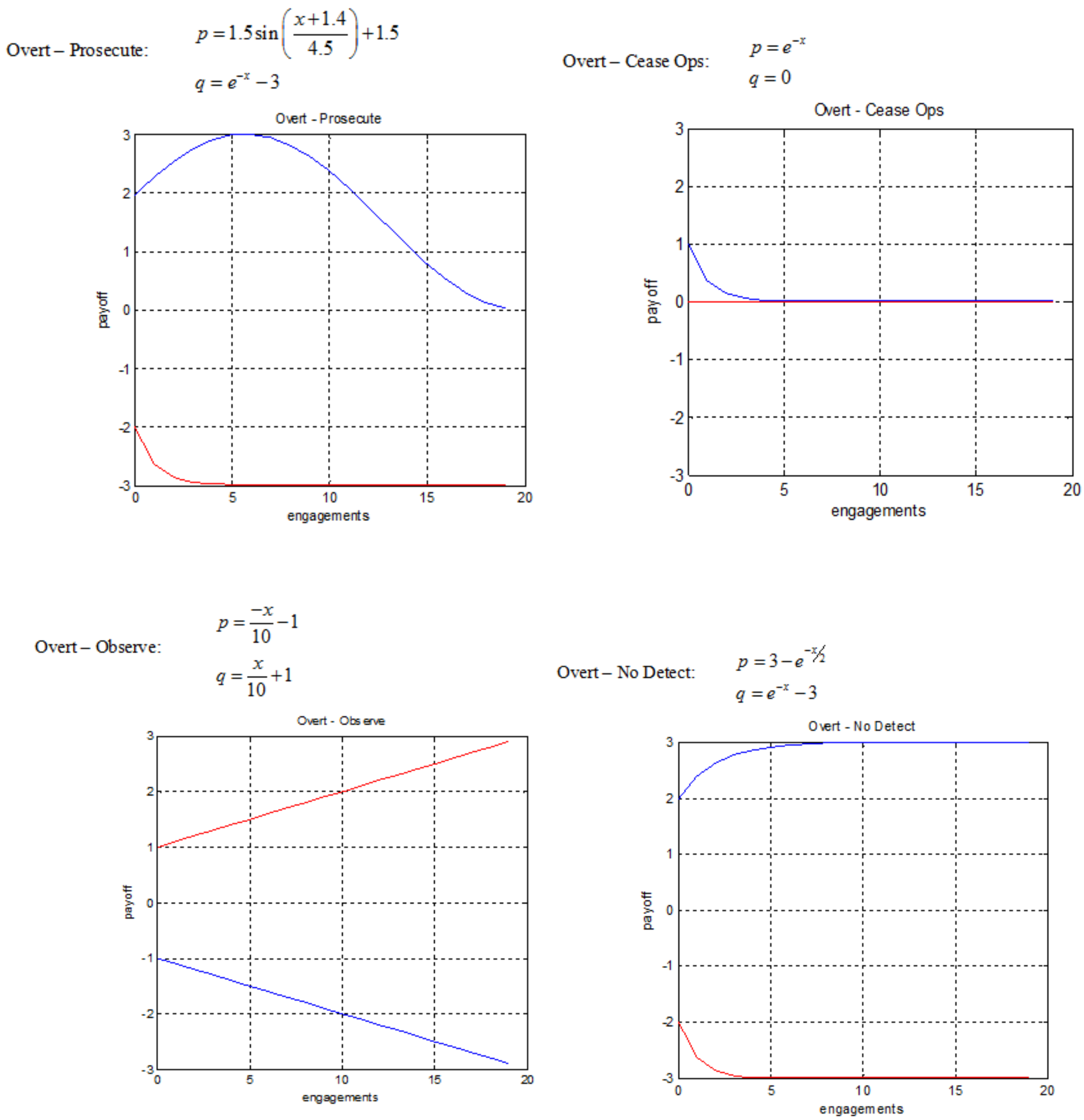


Figure 33. IO Assessment and Observation Payoff Relationships. The expressions and plots describe the change in Blue and Red payoffs over the course of multiple engagements, or over the course of time of employment of the decoy strategy.

The structure of the game is depicted as a sequential decision tree in Figure 34, with detection shown as a probabilistic event node. When analyzing the tree, the decision nodes are replaced with event nodes, and the probabilities on each branch varied to represent the range of mixed strategies employed by either side.

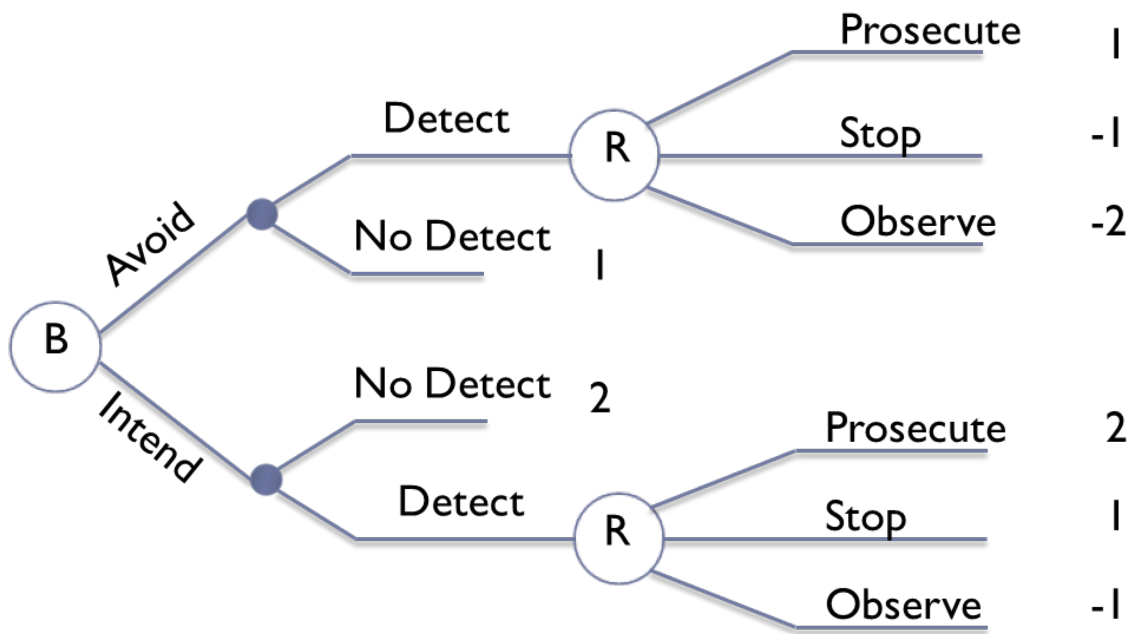


Figure 34. IO Sequential Decision Tree. The decision tree depicts the structure of the game, with Blue first choosing an employment posture followed by a probability of Red detection and a Red choice of response.

Because each branch has a definitive payoff and probability of occurrence given assumed mixed strategies for blue and red, the expected payoff of the game is a simple calculation of summing the probabilistic payoff of each branch. Mixed strategies are varied and the calculated payoff tabulated. Probabilities of detection for red against covert employments are assumed at 20% and overt employments are assumed at 95%.

The results of the game theory analysis are generated using the MATLAB code included in Appendix H. As shown in Figure 35, the results can be graphically represented by plotting payoff as a function of blue mixed strategy, with a result for each engagement and each red “aggressiveness” mixed strategy. Each data series represents an engagement, and the results are plotted for a course of 20 engagements against one red mixed strategy.

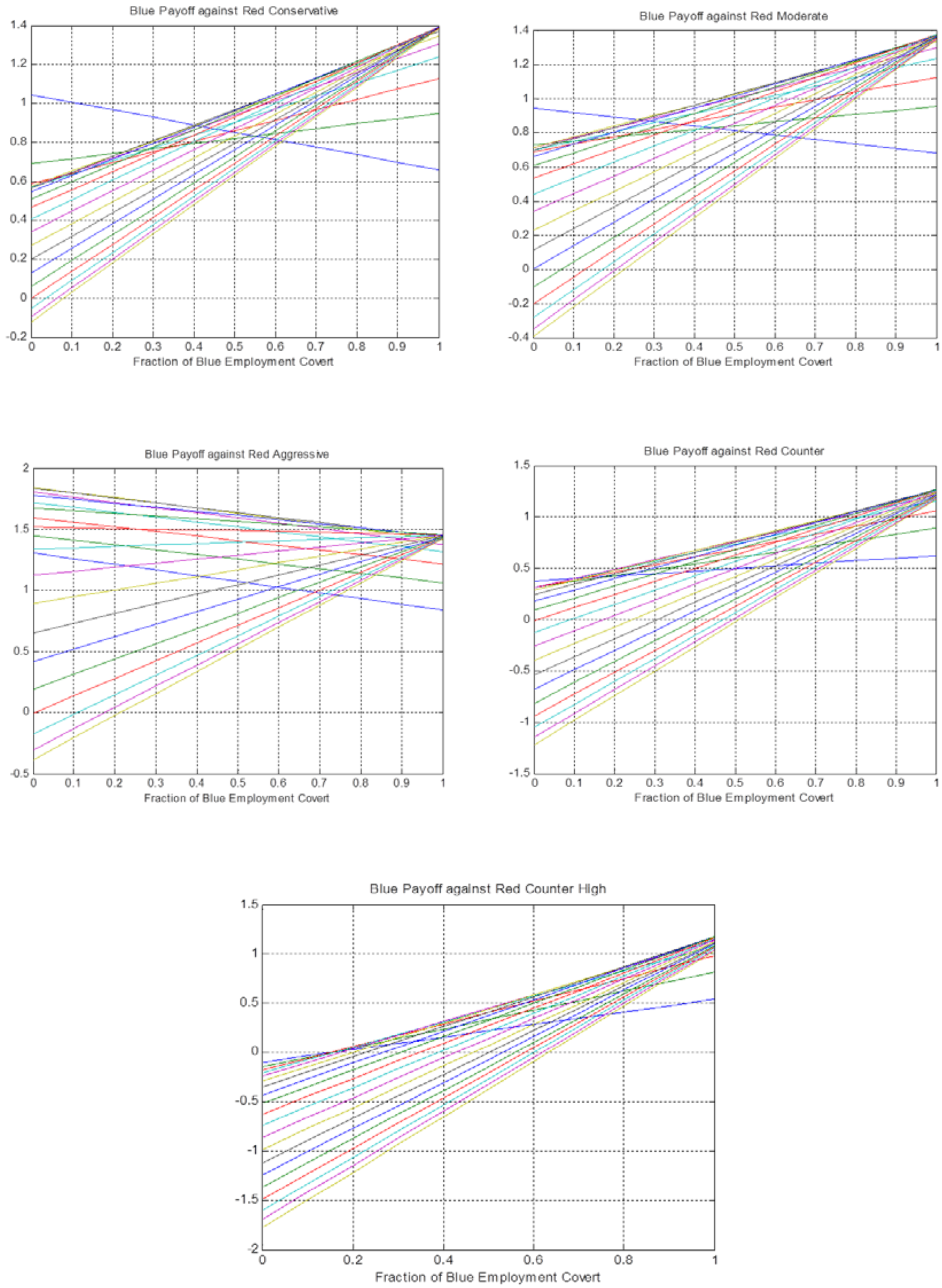


Figure 35. Payoff as a Function of Blue Mixed Strategy. The plots represent the expected payoff for Blue resulting from each decoy engagement as a function of Blue mixed strategy. Each line represents one sequential engagement. There is a separate plot for each Red mixed strategy.

Since each expected payoff is a strictly linear function of the specific result payoffs and probabilities, the distribution is always linear and not terribly sensitive in the region of assumed “reasonable” red aggressiveness strategies. The values in Table 9 were used as probability of red response for each level of aggressiveness.

Red Aggressiveness					
	Conservative	Moderate	Aggressive	Counter	Counter High
Prosecute	0.2	0.3	0.7	0.3	0.2
Cease	0.7	0.5	0.1	0.2	0.1
Observe	0.1	0.2	0.2	0.5	0.7

Table 9. Probabilities of Red Response for each Level of Aggressiveness. This matrix shows all considered Red mixed strategies for response to the decoy scenario.

The “Counter” and “Counter High” strategies were not initially included, but subsequently added to drive some variation in the response. These represent an increased willingness of the enemy to assume risk and attempt to “counter-collect” on the UUV.

The results of this analysis should inform how to select an appropriate mixed strategy for blue employment in order to maximize expected payoff while mitigating risk, and how that balance of employment should change over the course of multiple engagements. Specifically, by assuming a Red aggressiveness posture and plotting the results of specific ranges of engagements, Blue could determine the best mixed strategy to employ over the course of those selected engagements. Based on the shape of the total solution space, the point can be determined where Blue can employ a mixed strategy that has the greatest minimum payoff, which correlates to the lowest risk. For example, against the conservative Red strategy, this point is approximately 60% covert employment. Against the aggressive strategy, this point shifts to approximately 73% covert employment. Different criteria could be used to select the desired effect, and therefore best mixed strategy.

Conclusions: The summary conclusion of this analysis is embedded in the potential range of results for each scenario and the shape of the solution space. The data provide some intuition into the minimum and maximum payoff or utility and the factors

controlling the range of those results. A control payoff resulting from a traditional SSN collection unaided by UUV deception may be assumed, and the potential enhanced benefit assessed. Additional study of sensitivity of payoff functions, risk tolerance, and red mixed strategies may provide further insights.

In Figure 36, an example is portrayed by plotting all blue payoff results from the first ten engagements against the conservative, moderate, and aggressive red strategies.

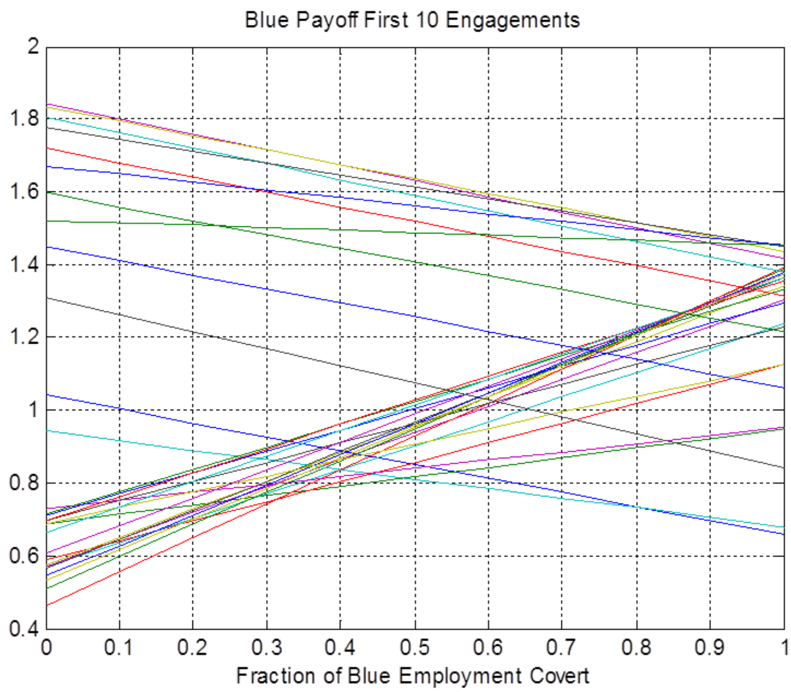


Figure 36. Blue Payoff vs. Red Conservative, Moderate, and Aggressive Strategies (10 Engagements). The first 10 engagements against the three basic Red response strategies result in the depicted composite solution space.

This shows the blue mixed strategy with minimal risk is to employ covertly about 50% of the time, which generates a potential maximum payoff of about 1.6, or approximately 86% of the global maximum in the result. Additionally, there are no negative payoffs in this solution space.

For comparison, the results against the same red strategies are plotted for all 20 engagements in Figure 37. It can be seen that safest blue mixed strategy has shifted

to the right, to about 65% covert employment. The range of possible payoffs has also extended to include negative values, while the global maximum payoff has not increased. Therefore, continued employment after the first ten engagements introduces new risk with no new gain. This type of analysis could inform how blue should adapt its strategy over the course of a series of engagements. Depending on the scenario being considered, a selection of aggressiveness strategies and specific engagement series could be analyzed. This provides a framework to consider the sensitivity of the result with respect to the assumption of enemy posture, and the overall length of the campaign.

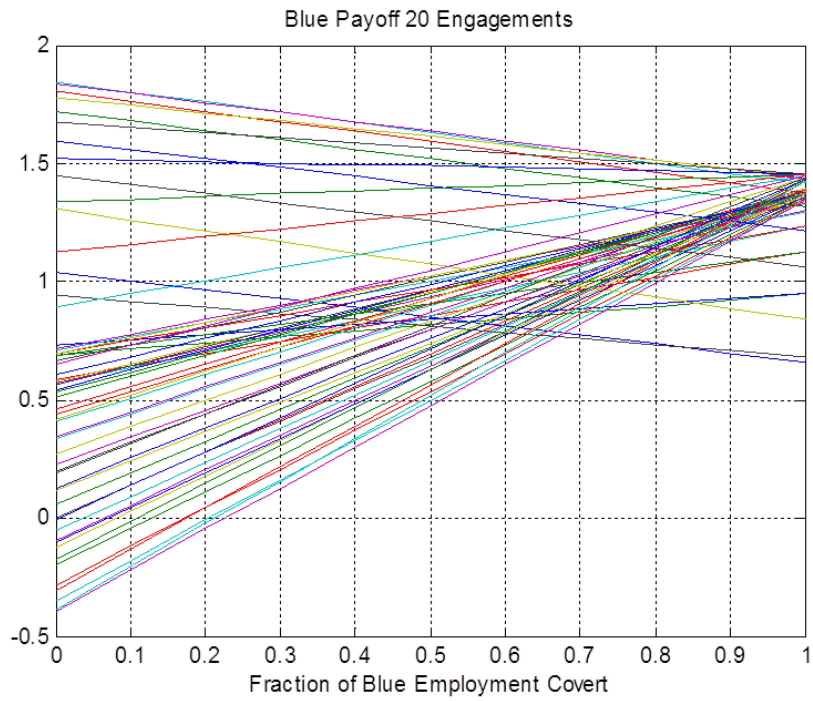


Figure 37. Blue Payoff vs. Red Conservative, Moderate, and Aggressive Strategies (20 Engagements). The payoff from 20 engagements against the three basic Red response strategies are shown together, creating the depicted composite solution space.

This model generates many opportunities for further analysis. All payoff functions and probabilities were assumed with some discussion and input from SMEs, but more rigorous investigation to determine more supported values could bring validity to the result. Alternatively, a more in-depth analysis of the impact of risk tolerance would add to the value of the model. Some investigation into the impact of risk variation over the course of the campaign may yield interesting results. The same approach could be

employed to investigate the impact of changing red mixed strategies over the course of a series of engagements. Several options are presented in this analysis, but further study could provide valuable insights into which strategies should be analyzed at different stages of the campaign.

b. IO Distraction UUV Model

Utilizing MANA V, agents are created to represent the SSN, UUVs, red force ASW assets, and neutral maritime traffic. The UUV agents for this scenario adhere to the overt employment description described previously. They are intended to be detected to draw attention away from the operating SSN. As a result, their vulnerability to ASW sensors is systematically higher than that assumed for UUV agents in other mission areas. The UUV agents are subject to the constraints assumed for 21” vehicles in order to minimize cost, as these UUVs are intended to be expendable.

The scenario geometry lays out an assumed target location on land which is monitored by a coastal radar and the adjacent waters patrolled by surface combatants. A maritime patrol aircraft and ASW-equipped helicopter perform periodic patrols. One red SSN is underway patrolling the operational area randomly.

Factors to be studied include the speed profile of the UUV, the maritime traffic density, and the number of UUVs employed. All factors will be analyzed at all levels comprising a full factorial experiment. The scenario will be evaluated for the SSN without UUVs as the control. Due to the endurance limitation of smaller UUVs, the decoys are launched from around 40 miles from shore. The decoys attempt to draw the security forces to the north while the SSN conducts it mission in the southern area of the coast. The geometry is illustrated in Figure 38.

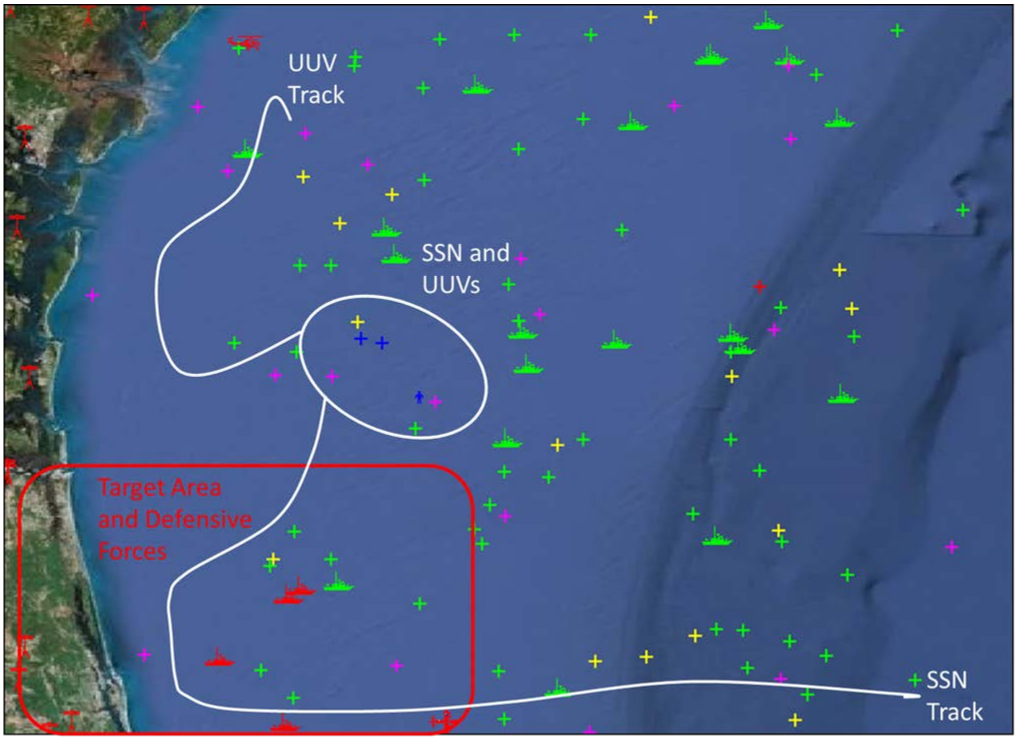


Figure 38. IO UUV MANA V Distraction Mission Profile. Objective of the simulation is for the UUVs to draw enemy forces to the north while SSN conducts missions or exfiltration to the south.

The results in Table 10 and Figure 39 show the number of SSNs killed by each type of Red platform during 500 replications of each scenario. Of note, Red surface vessels recorded no kills against the Blue submarine.

	Sub		1 UUV Constant		1 UUV Sprint		2 UUVs Constant		2 UUVs Sprint	
Traffic Density	Low	High	Low	High	Low	High	Low	High	Low	High
MPA	15	16	24	11	16	14	13	9	18	10
Helo	8	9	10	13	12	11	16	6	5	7
Sub	5	10	1	5	1	2	3	5	2	5
Merchant	2	0	0	0	1	0	0	1	0	0
Total Subs Killed	30	35	35	29	30	27	32	21	25	22
σ (+/-)	5.3	5.7	5.7	5.2	5.3	5.1	5.5	4.5	4.9	4.6
95% CI (+/-)	10.4	11.2	11.2	10.2	10.4	9.9	10.7	8.8	9.6	9.0

Table 10. SSNs Losses With/Without UUV Distraction (500 Replications). Total submarines killed tend to decrease as more UUVs are utilized for distraction. UUVs that are more survivable (sprint/obstacle avoidance) also tend to increase submarine survival. This is due to the ability of the UUV to conduct distraction operations for a longer duration.

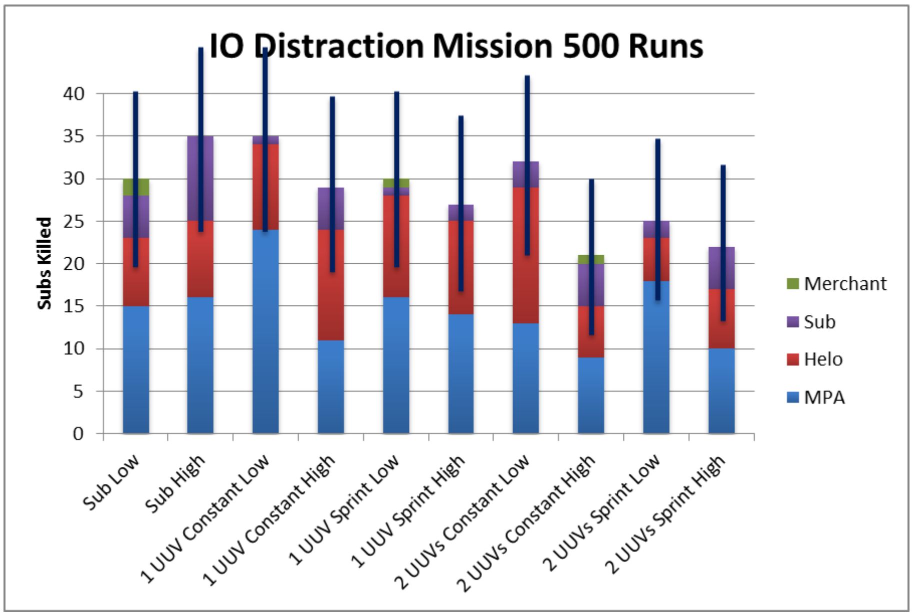


Figure 39. Graphical Representation of SSNs Losses With/Without UUV Distraction. In all but one case the addition of UUVs improves submarine survivability.

There is not a great deal of variability in the results, the difference in survivability between the best and worst scenarios are less than 3%. Many more replications are required to validate the significance of variation in the results. The 95% confidence intervals portrayed on Figure 39 show the range of statistical variability involved. Further analysis is also required to examine the effect of different tactics with regard to UUV and submarine tracks. This model did not address the tactical employment as a factor. Variation in the UUV profile could also be analyzed in greater detail. The decoy UUVs were simulated with a constant overt profile. Further studies could evaluate the benefit of a more varied posture to retain the attention of red ASW forces for a longer period.

c. Key IO Modeling Takeaways

- UUVs force the opposition to expend resources and time to identify and prosecute the multiple threats presented
- Using UUVs for decoy and distraction operations seems to suggest improved SSN survivability, but more analysis is required to confirm
- Employing two UUVs for distraction provides improved survivability compared to one UUV
- It is typically beneficial for the UUVs to have a sprint evasion capability otherwise referred to as object avoidance

4. Offensive Attack Operations

Attack UUV modeling is conducted to examine the contribution of UUVs in an attack role. While conducting the modeling it became readily apparent that UUVs do not currently possess the endurance and maneuvering characteristics necessary to conduct anti-submarine and anti-surface warfare in a traditional sense. The traditional track and trail and long decision timeline simply does not fit for the type of combat that is observed with armed UUVs. Combat occurs when UUVs sense a target of opportunity, and then make a decision on whether or not to engage the target. This concept of operations is heavily reliant upon the pillars of multi-sensory input, advanced processing, and communications. When the UUV gains contact via sensory inputs, it may have to match the signal to a library and discern if that is a signal of interest. This is also known as

Autonomous Target Recognition (ATR). An example of this is a UUV with visual, acoustic and ESM sensors that conducts data fusion to utilize all three data sources. Advanced onboard processing and data storage facilitate this capability. Without completely reliable data processing or sensing systems human-in-the-loop may be required to prevent the unintended targeting of innocent vessels. This scheme of engagement would require an over the horizon communication system to transfer data of interest to a human decision maker for the final engagement approval.

The concepts examined in this model include recoverable UUVs of 48” and 60” diameter that represent a notional LDUUV and a 21” vehicle modeled after the proposed Modular Undersea Heavyweight Vehicle (MUHV). To model offensive mining a unique UUV glider style mine was modeled. This concept is modeled as a 21” vehicle that exhibits the characteristics of a sea glider in a search mode and retains propeller propulsion for a higher speed terminal phase. When a submarine operates in conjunction with the UUV the submarine operates on the periphery of the UUV operating area and conducts a combat patrol as a transit search.

The 48” UUV has one Mk-46/54 equivalent weapon embarked for use and the 60” UUV has two Mk-46/54 equivalent weapons available for use. The recoverable vehicles conduct a transit search tactic. Two vehicles of the same size conduct independent patrols of approximately 170 NM in each simulation. This distance was chosen based upon the endurance limitations of the vehicles.

The MUHV is a configurable vehicle that is based on the Mk-48 torpedo (OPNAV N97 2012). Four vehicles are utilized in during each mission. The vehicles are expendable. Each vehicle conducts an independent transit of approximately eighty miles. When the vehicle reaches the final waypoint it loiters until onboard fuel is exhausted. When onboard fuel is exhausted the vehicle scuttles and is lost. If an enemy surface combatant or submarine is encountered the vehicle increases speed to twenty five knots and conducts a terminal attack.

The 21” glider mine is modeled as a weapon that is deployed in pods of variable size. The weapon has half of the energy available as compared to the 21” MUHV but only consumes 25% of the energy of the MUHV. The patrol length is approximately 100

NM. These weapons could be delivered by a submarine, surface or air delivered. The mine transits like a glider at approximately two knots and has a terminal homing phase of fifteen knots. The weapon exhibits the same detection characteristics as the other UUVs but requires two hits to kill a surface vessel, and one hit to kill a submarine. The deployment scheme in these scenarios is in three salvos, or pods of varying size.

Analysis of the results of the simulation is based upon the measures of effectiveness for attack vehicles. The primary measures of effectiveness analyzed are:

1. Enemy casualty rate
2. UUV survival rate
3. Friendly submarine survival rate

In tandem with friendly and enemy casualty rates, exchange ratios are utilized across variable contact densities. Full factorial experiments are executed for the attack missions with 100 replications of each simulation. In some areas, further simulation with 500 replications is conducted to investigate the results and attempt to gain statistical significance.

a. Enemy Casualty Rates and Combat Exchange Ratios

Enemy loss rates as well as combat exchange ratios are investigated in this model. In the submarine only scenario, exchange ratios are first examined to inspect for simulation realism. To begin, exchange ratios are highly dependent upon contact density. The exchange ratios also vary greatly between surface combatants and submarines. This appears to be a function of the stealth of the submarine and its reduced acoustic signature. The enemy submarine to friendly submarine exchange ratio is 6:1. The enemy surface combatant to friendly submarine exchange ratio is 23:1. The total consolidated enemy threat to friendly submarine exchange ratio is 39:1. These exchange ratios are then compared against simulations that include UUV contributions.

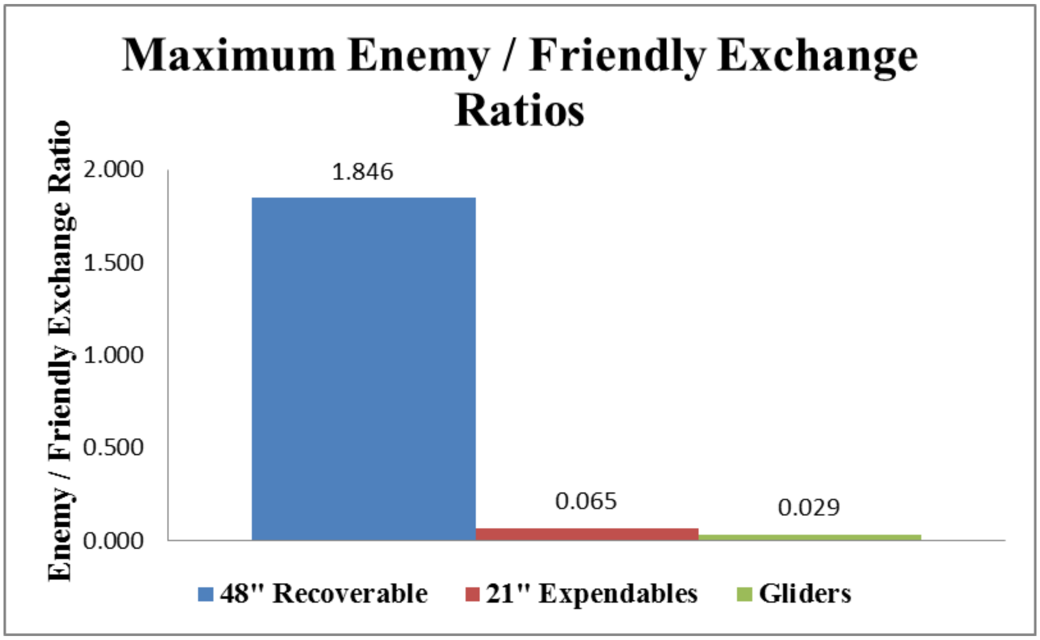


Figure 40. UUV Combat Exchange Ratios. The larger and more capable UUVs provide substantially more combat capability than smaller and less capable UUVs. This is primarily a result of the increased sensor capabilities of the larger UUVs.

The results in Figure 40 show that there is positive effect on combat exchange ratios when UUVs are used in conjunction with an attack submarine. The greatest improvement occurred with the addition of a highly capable 48” diameter UUV that increased combat exchange ratio of friendly submarines by almost two.

Further analysis of the submarine survivability trends with 500 replications of a friendly attack submarine operating in conjunction with a 48” diameter UUVs showed that there appears to be a positive relationship with submarine survivability. When submarines are operating without UUVs the loss rate is approximately 8% per mission. With UUVs the number drops to about 6.5% per mission. The data appears to show a difference in submarine survival rates when UUVs are utilized, however a two tailed t-test determined that the difference in the means is not statistically significant.

The exchange ratios also show that while an attack UUV is viable, the concept would require large numbers of small UUVs to conduct an effective campaign in an A2AD environment. Analysis of the 21” MUHV concept shows an enemy to UUV exchange ratio of approximately 0.065:1. If this weapon is used in large numbers in a

coordinated attack of a defended area, enough enemy casualties may be generated to justify the cost of that many expendable UUVs. The data is analyzed using a binomial distribution (shown in Figure 41) to investigate this concept. The probability of success per attempt, or per UUV, is utilized to determine how many attempts are required to achieve *X* number of enemy casualties or greater. This is expressed as X, P(X≥k) = 1-P(X≤(k-1)). For example, with the success rate of 0.0625 on any given attempt, the P(≥1 enemy kill in 25 trials) = 1-P(0 kills in 25 trials) = 0.80. The results show that large quantities of expendable UUVs are required to have a significant impact on enemy operations.

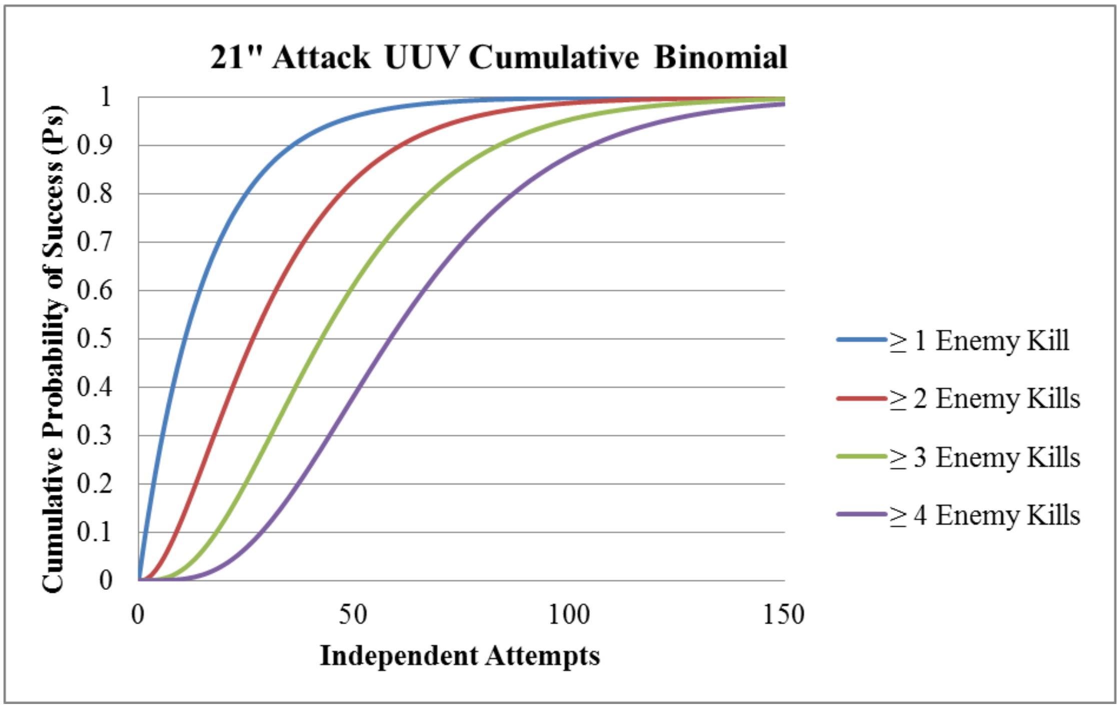


Figure 41. 21” Expendable Attack UUV Enemy Casualty Binomial. This figure is used to show the number of 21” UUVs that must be deployed (Attempts) in order to achieve a desired cumulative probability of mission success of killing a variable number of enemies.

The number of enemy casualties per mission is an even more telling measure of UUV effectiveness. For example, Figure 42 shows that the deployment of four 48” UUVs may result in one additional enemy casualty. While that may not seem

significant, imagine that the one extra casualty is an enemy diesel or nuclear submarine operating in close vicinity to friendly HVUs.

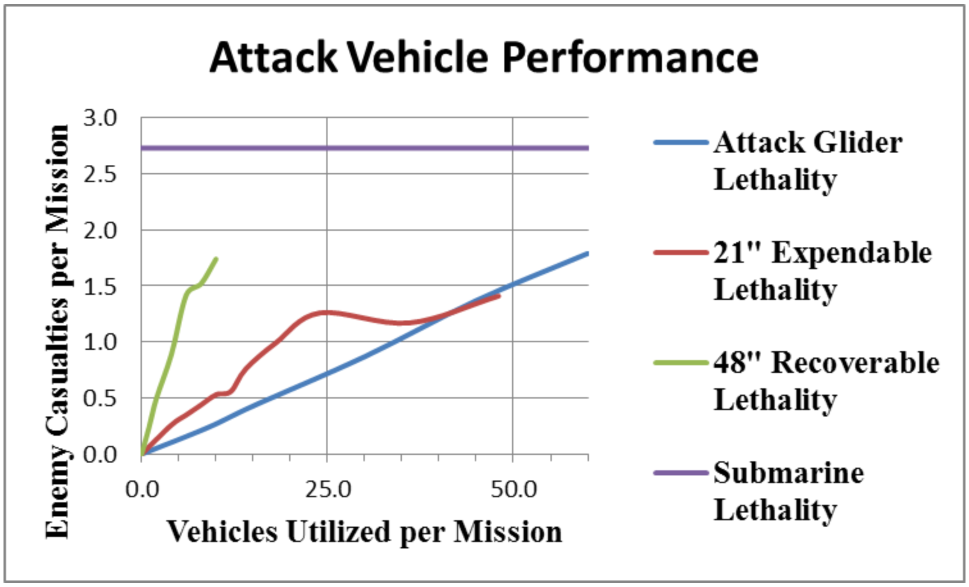


Figure 42. Enemy Casualties per UUV Deployed. Nearly 35 expendable gliders and 20 expendable 21" UUVs are required to achieve the same number of enemy casualties per mission as 4 recoverable 48" UUVs.

By increasing the number of smaller less capable UUVs, there is potential to increase the average number of enemy casualties as shown in Figure 43. It is important to note that the modeling assumed that all UUV variants are equipped with autonomous target recognition (ATR) systems to target enemy combatants rather than civilian maritime traffic. ATR systems may or may not be feasible for smaller UUVs such as gliders, depending on future technological maturation.

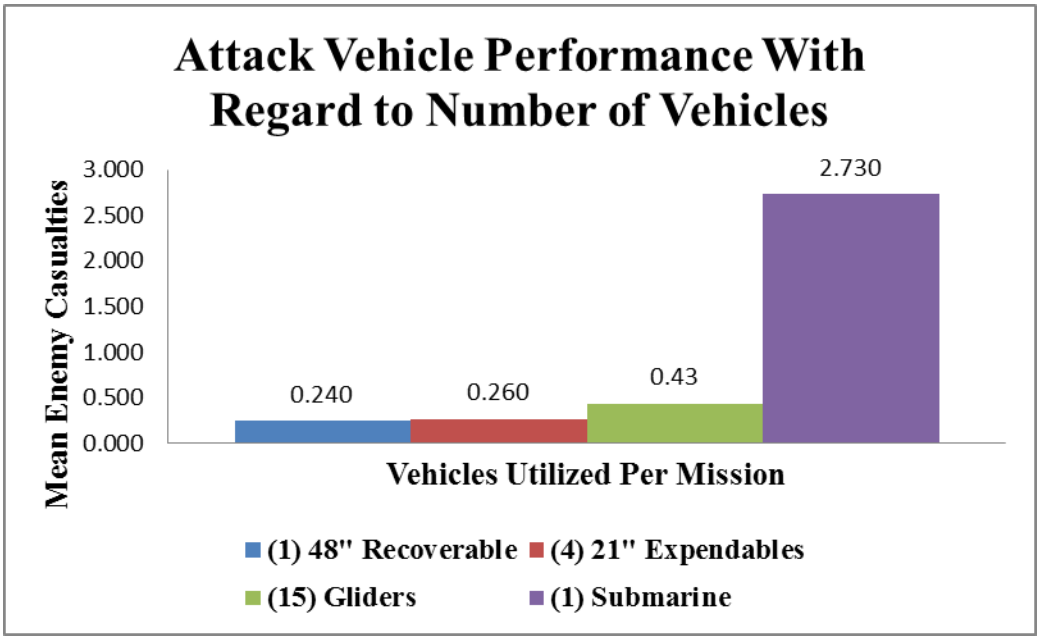


Figure 43. Attack Vehicle Performance Based on Salvo Size. By increasing the numbers of smaller UUVs, greater numbers of enemy casualties are possible, compared to that of fewer LDUUVs.

In regards to the proposed force structure for attack UUVs, required quantities and capabilities of each variant must be subjected to a thorough analysis of alternatives and cost versus benefit analysis to determine optimally system selection.

b. Attack UUV Loss Rates

Another critical area of interest in UUV operations is avoidance behavior. In our modeling the UUV operations with a constant speed of four knots and a sprint object avoidance speed of eight knots for a six minute duration were compared. What was found was that UUVs with avoidance behavior were significantly more survivable. Figure 44 shows the losses for the constant speed UUVs and Figure 45 shows that the losses of UUVs that incorporate the eight knot sprint obstacle avoidance are much lower than that of the constant speed variants.

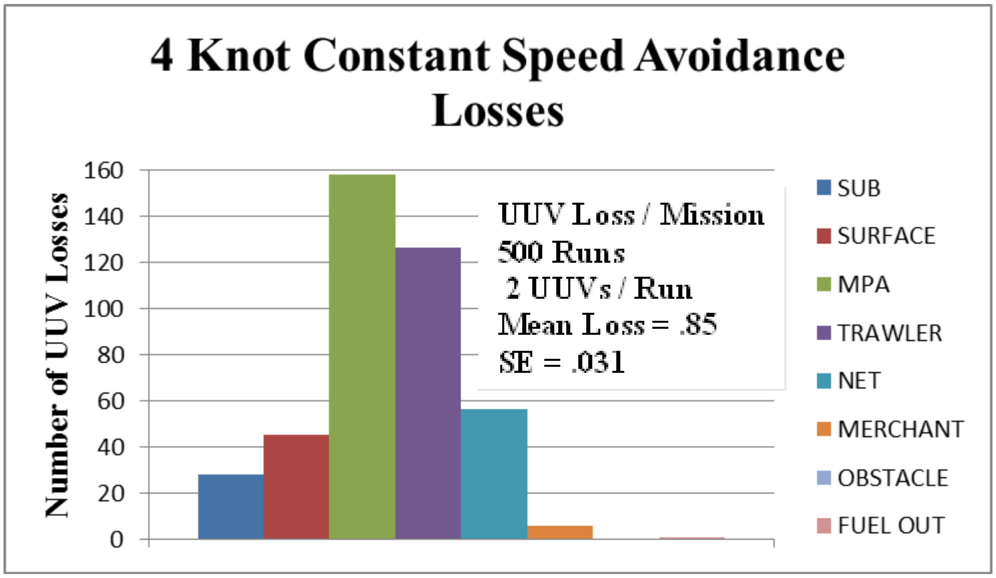


Figure 44. UUV Losses Without Object Avoidance. UUVs without obstacle avoidance transit at constant speed and direct routes from point A to point B. When compared to Figure 45 UUV loss rates are much higher for UUVs without object avoidance systems.

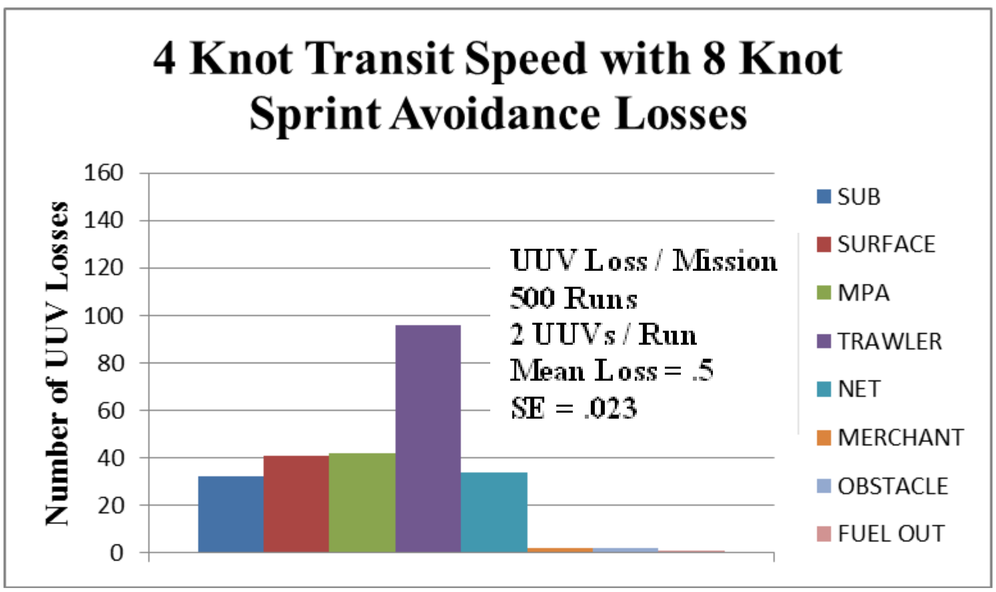
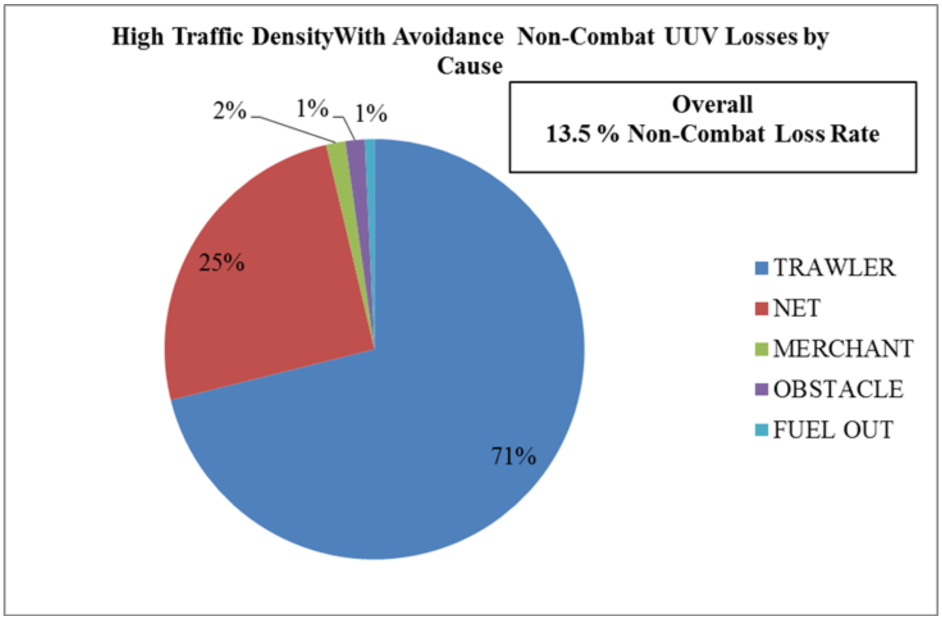


Figure 45. UUV Losses With Object Avoidance. When compared to Figure 44 the UUVs that incorporate significant obstacle avoidance are much more survivable than UUV models that do not use course and speed adjustments to avoid contacts and obstacles.

Detailed analysis on loss by cause was also conducted with this analysis. Loss by cause is important to determine the true threats to UUV operations. UUV loss rates are examined as a result of combatants and non-combatants. The UUV loss rate when combatants are included is 25 percent and 13.5 percent from non-combatants alone. A significant discovery from the modeling is that non-combatants are more of a threat to UUVs than combatants. In particular, trawlers are especially lethal to UUVs, accounting for 71 percent of non-combatant UUV casualties and 38 percent of UUV casualties from all sources. Drifting nets also pose a significant problem, accounting for 25 percent of all non-combatant UUV casualties and 14 percent of UUV casualties from all sources. Figure 46 graphically represents the proportions of sources of UUV casualties.



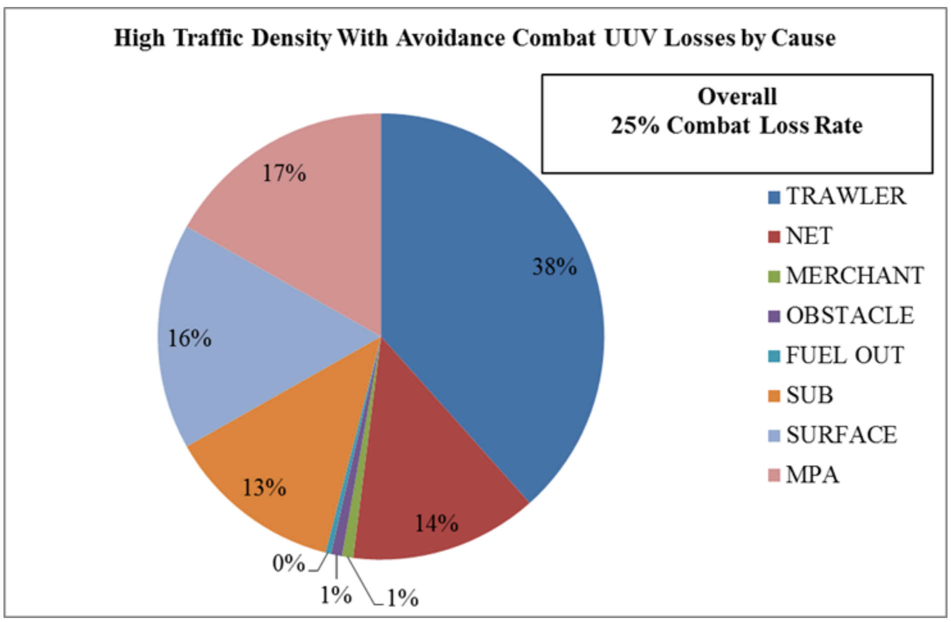


Figure 46. Proportion of Sources of UUV Casualties. Non-combatants result in a 13.5% UUV loss rate, with the proportion of each source shown in the chart. When combatants are included, the overall UUV loss rate is 25%, with the proportions shown in the bottom chart.

c. *Offensive Mine Modeling*

Attack modeling of a glider type mine is inspired by the 21” MUHV analysis that showed that an expendable vehicle could possibly be a valid approach to the attack mission area. Gliders are examined in particular due to low power consumption rates, and the inability of other mining platforms such as aircraft to operate in an A2AD environment. Also, traditional mine warfare modeling is conducted better with other simulation programs such as GAMET, which is produced by Naval Surface Warfare Center, Panama City. To compare the effectiveness of a glider mine as compared to the MUHV concept, a binomial analysis is conducted in the same manner as a 21-inch diameter attack UUV. This analysis is shown in Figure 47.

Results show that even more glider mines would be required to conduct a similar mission. Almost 50% more UUVs are required when conducting a glider mine attack as opposed to a MUHV attack. While this may seem disconcerting and disappointing, it is of note that two hits are required to kill surface vessels with a glider mine as opposed to one for all other attack UUV variants. We see here that a less capable weapon, and theoretically less expensive, would be able to execute this mission set if employed in the sufficient numbers.

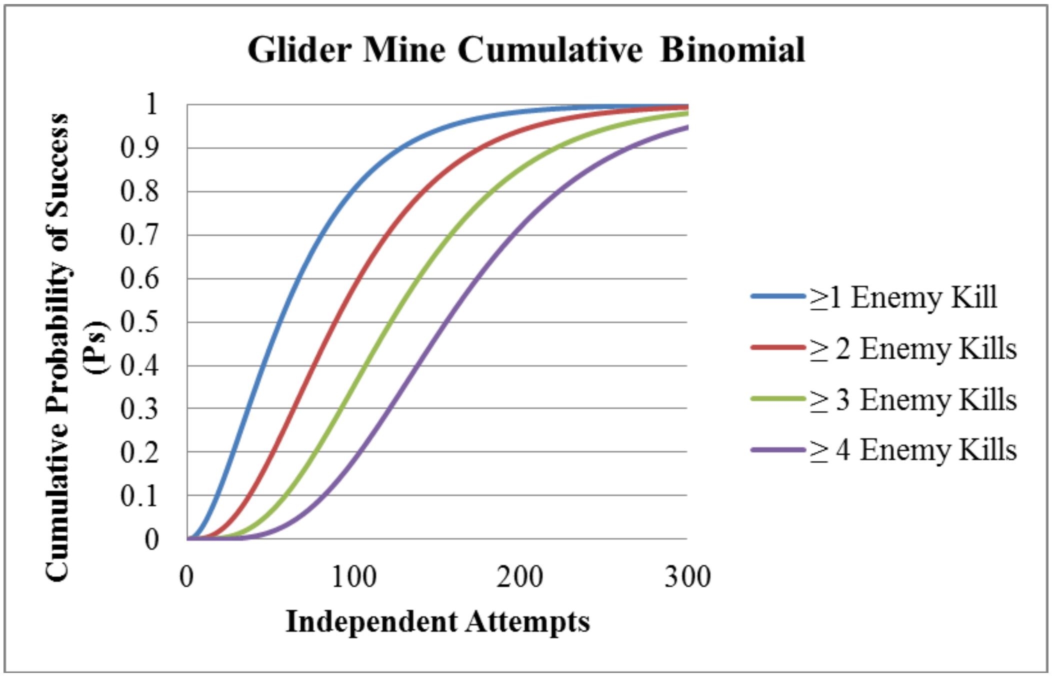


Figure 47. Expendable Glider Attack UUV Enemy Casualty Binomial. This figure is used to show the number of glider mines that must be deployed (Attempts) in order to achieve a desired cumulative probability of mission success of killing a variable number of enemies.

To further examine the appropriate pod size for glider mine employment the number of glider mines employed is compared against the number of enemy casualties as shown in Figure 48. The figure shows that the three pod tactic utilized influences combat effectiveness. The greatest effectiveness observed is when pod size was between 15 and 20 mines for a total number of 45 to 60 mines.

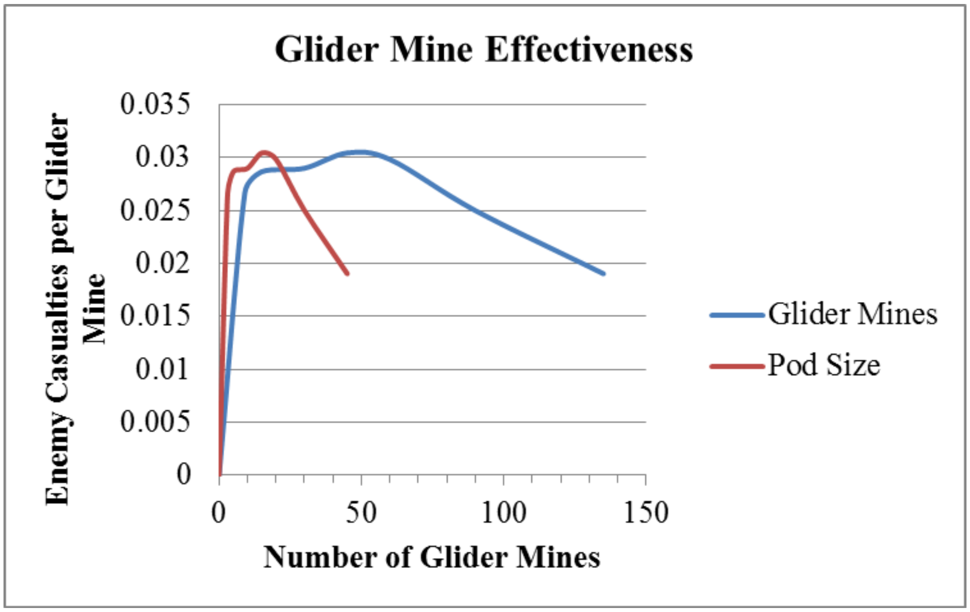


Figure 48. Offensive Glider Mine Effectiveness. The red curve represents the number of gliders deployed per pod. The blue curve represents the total number of gliders deployed. Three pod salvos of approximately 15–20 gliders each, for a total of approximately 45–60 gliders, provides the greatest number of enemy casualties.

d. Key Offensive Attack Modeling Takeaways

- UUV attack missions are viable but best conducted with large numbers of expendable UUVs or small numbers of highly capable UUVs outfitted with multiple weapons
- While the ASW/ASUW mission set may be viable, this is a mission set that may be best conducted utilizing an SSNs
- UUV maneuvering behavior and autonomy can have a significant impact on the UUV survivability
- UUV variants used in an offensive mining role show significant military capability

5. Mine Countermeasures

Mine countermeasure missions consists of two distinct mission profiles: overt MCM, where concealment is not a priority, and covert, where concealment is of the highest priority. Initial analysis of these two mission profiles revealed that the UUVs undersea stealth capability make it well suited to conduct covert MCM missions in A2AD environments.

a. Covert MCM Q-Route Modeling

Q-route mapping for follow-on forces in an A2AD environment is critical to reducing the probability of kill for high value units (HVUs) transiting known minefields. A Q-route is defined as a system of preplanned shipping lanes in mined or potentially mined waters used to minimize the area the mine countermeasure commander has to keep clear of mines to provide safe passage for friendly shipping and HVUs.

The MANA V MCM scenario models the mapping of a Q-route for a HVU transit through a 20 NM by 10 NM minefields that simulates many choke point transit areas around the world. Two different environments were setup in the model. One was a low density and low-tech mine environment, which consisted of 25 "low-tech" mines randomly distributed throughout the minefield. The second environment was a high density and high-tech mine environment, which consisted of 50 "high-tech" mines randomly distributed throughout the minefield. Variable quantities of UUVs transit the minefield searching for mines. When mines are discovered, their location is relayed back to the HVU. The HVU then follow the path taken by the UUVs avoiding any discovered mines while not venturing too far off the searched path as shown in Figure 49.

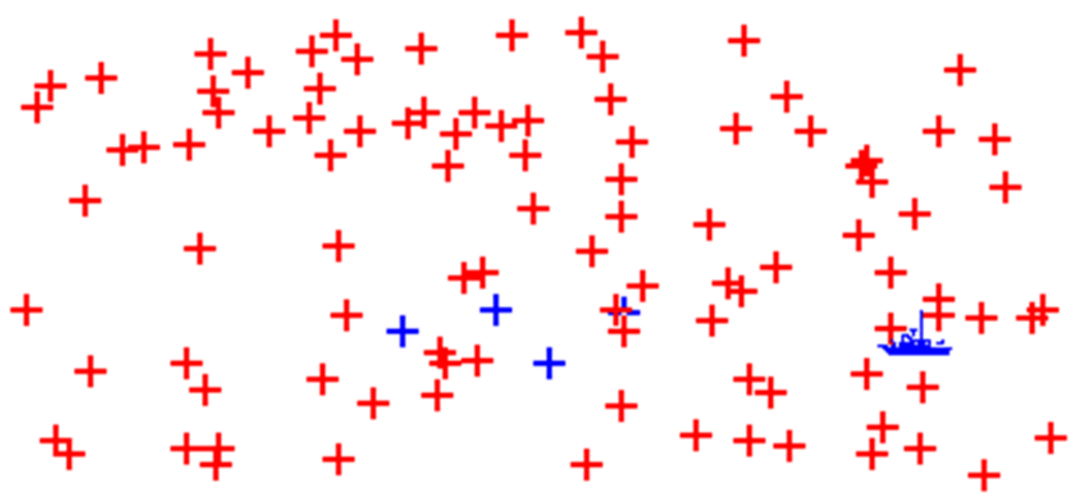


Figure 49. MANA V MCM Q-Route Mapping Scenario. Red (+) signs indicate mines, the blue (+) signs indicate UUVs, and the blue ship indicates an HVU. The UUVs transit covertly ahead of the HVU localizing and transmitting mine positions to the HVU. The HVU then attempts to transit the minefield by avoiding known mine positions. In some

cases the UUVs are equipped with the capability to neutralize mines.

The low-tech mine is modeled around the widely available Italian Manta Mine (Globalsecurity 2002). Assumptions in this model are that the mine would have a 200-meter range that spans 360 degrees, a 90% probability of detecting a HVU, and would not be able to detect and target a UUV. The high-tech mine essentially doubled some of the characteristics of the low-tech mine. Assumptions are that the high-tech mine would have a 400-meter range that spans 360 degrees, a 90% probability of detecting a HVU, and a 30% probability of detecting a UUV. In all of the mine models, it is assumed that if a mine detects a target that target is destroyed, or in other words the mine's probability of kill is 100% if it detects a target.

The mine detection equipment is based on information received from the Naval Surface Warfare Center Panama City Division (Rodriguez 2013). It is assumed that there is no difference between the sensor on the UUV or on the HVU when equipped. It is also assumed that the sensors have a range of 800 meters that spans a 180-degree arc (ninety degrees from the bow to the beam on each side) and the sensors have an 80% probability of mine detection.

Speed, navigational accuracy, and safe distance from mines are important factors when transiting a Q-route. A ship transiting a Q-route needs to move slow enough to be able to detect mines with enough time to maneuver, but not so slow such that the ship would not have enough wash over its rudder to be able maneuver sufficiently. In the mine model it was assumed that the UUV would transit the minefield at 3 knots and the HVU would follow at the same speed. Additionally, the model was setup for the HVU would try to stay at least 1000 meters away from any discovered mines.

In some runs the UUV is equipped with a weapon that can neutralize or destroy a mine. This weapon has a 90% probability of kill against a mine. It is assumed that the UUV is not equipped with a logic model to prioritize mine clearance. Its behavior is setup to attempt to neutralize the first mine it detected.

The measures of effectiveness and performance for this model are:

- HVU Survival Rate: Percentage of times the HVU is not detected by a mine. This was considered the most important measure.

- Q-Route Success Rate: Percentage of time the HVU was able to reach its intended destination. A failure occurred when the HVU was sunk or could not find a way through the minefield.
- UUV Survival Rate: Percentage of the total UUVs that were not detected by a mine.
- Scenario Run Time: Average time it took to complete a successful Q-route based on the number of successful Q-routes.

15 variations of the scenario are run in both environments with 500 runs for each variation. Variable factors include the number of UUVs deployed, localization only or combined mine neutralization capability (shots), number of shots available for each UUV, and number of passes that UUVs make through the minefield prior to HVU entrance. MANA V data results are included in Tables 11 and 12. Graphical representations of this data are illustrated in Figures 50 and 51.

Low-Tech Low Density Minefield Results:

	HVU Survival	Q-route Success	Average Time
HVU No Sense	50.40%	50.40%	11.71
HVU Sense	71.40%	71.40%	11.88
UUV Only	78.00%	72.80%	12.47
UUV + HVU	87.00%	79.20%	12.65
2 UUVs	88.60%	75.40%	12.75
4 UUVs	94.40%	76%	12.91
6 UUVs	97.40%	75%	13.05
8 UUVs	98.80%	76%	13.15
UUV 1 Shot	83.40%	76.80%	12.33
UUV 2 Shots	85.40%	80.20%	12.11
2 UUVs 1 Shot	87.60%	78.00%	12.37
2 UUVs 2 Shots	86.80%	81.40%	12.14
2 UUVs 4 Shots	90.20%	90.20%	11.75
2 UUVs 2 Passes	90.60%	79.20%	25.26
4 UUVs 2 Passes	95.20%	77.20%	25.35

Table 11. MANA V Low-Tech Low Density Minefield HVU Survivability and Q-Route Data.HVU survival is the rate at which the HVU remains undetected by any mines while transiting minefield. Q-route success is rate at which HVU is able to reach intended destination. Average time is related to length of time it takes for the HVU to transit the minefield.

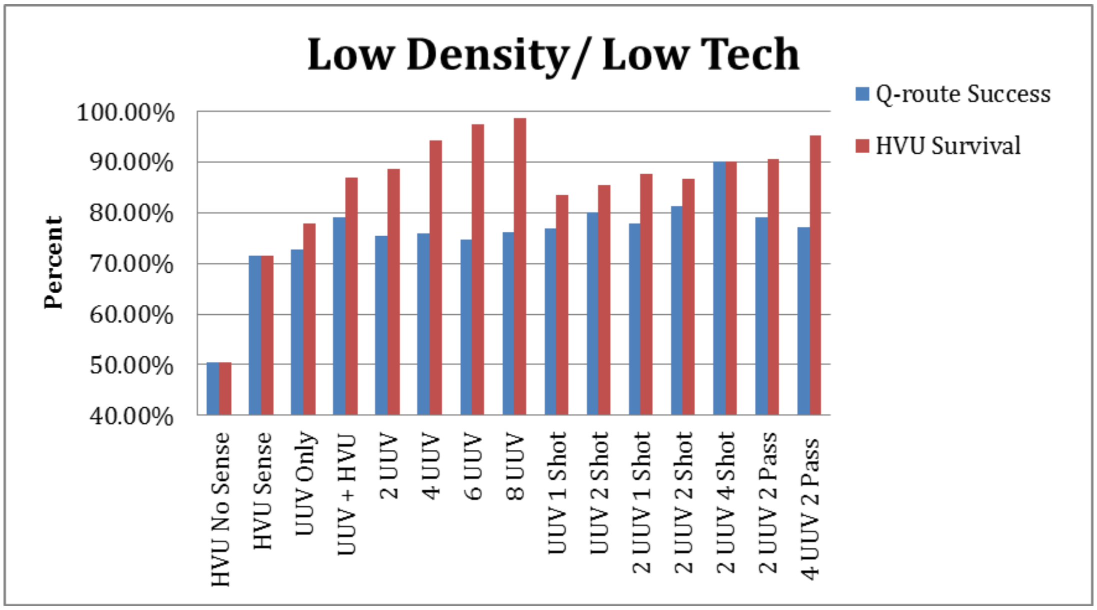


Figure 50. MANA V Low-Tech Low Density Minefield HVU Survivability and Q-Route Success. 10 x 20 NM minefields with 25 mines. Data shows that HVU survival increases as more UUVs are deployed to localize mines. Data also shows that mine localization with multiple UUVs is more effective for HVU survival than fewer UUVs equipped with mine neutralization capabilities.

High-Tech High Density Minefield Results:

	HVU Survival	Q-Route Success	UUV Survival	Average Time
HVU No Sense	1.00%	1.00%	N/A	11.8
HVU Sense	9.80%	9.80%	N/A	11.92
UUV Only	22.60%	13.00%	51.60%	13.11
UUV + HVU	35.20%	23.00%	48.40%	13.25
2 UUVs	40.00%	19.20%	50.60%	13.42
4 UUVs	65.40%	29.80%	48.80%	13.96
6 UUVs	78.20%	32.40%	44.70%	14
8 UUVs	83.00%	32.00%	44.40%	14.2
UUV 1 Shot	28.20%	16.80%	56.40%	12.81
UUV 2 Shots	25.80%	18.20%	61.60%	13.02
2 UUVs 1 Shot	42.40%	25.40%	55.60%	13.1
2 UUVs 2 Shots	45.00%	28.20%	62.90%	12.88
2 UUVs 4 Shots	49.80%	41.00%	69.60%	12.46
2 UUVs 2 Passes	49.00%	22.40%	19.00%	25.56
4 UUVs 2 Passes	74.40%	35.00%	17.45%	25.53

Table 12. MANA V High-Tech High Density Minefield HVU Survivability and Q-Route Data. HVU survival is the rate at which the HVU remains undetected by any mines while transiting minefield. Q-route success is rate at which HVU is able to reach intended destination. Average time is related to length of time it takes for the HVU to transit the minefield.

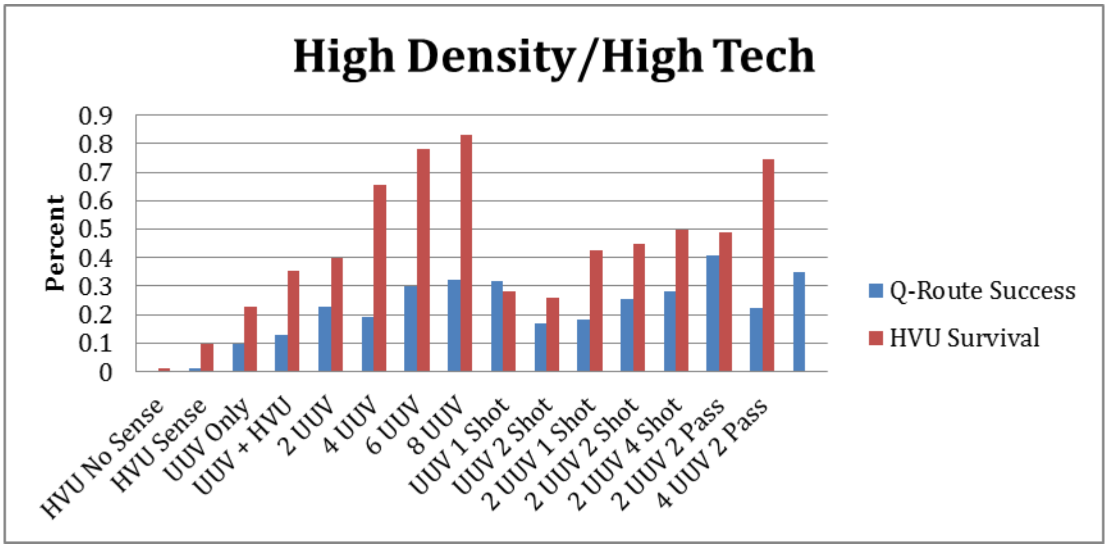


Figure 51. MANA V High-Tech High Density Minefield HVU Survivability and Q-Route Success. 10 x 20 NM minefield with 50 mines. Data shows that HVU survival increases as more UUVs are deployed to localize mines. Data also shows that mine localization with multiple UUVs is more effective for HVU survival than fewer UUVs equipped with mine neutralization capabilities.

The results of the mine models suggest that larger quantities of UUVs that are not equipped with a neutralization capability are more effective than a smaller number of more capable UUVs equipped with neutralization capability. The neutralization capability did increase the Q-route success percentage; however HVU survival rate is the most important measure and the neutralization capability had little impact on HVU survivability. Increasing the number of passes the UUV does through the minefield increases the HVU survival rate but comes at a cost to UUV survival rates. Based on time required, 21-inch diameter UUVs are sufficient to complete this mission based on endurance analysis.

b. *Key Covert MCM Modeling Takeaways*

- Larger quantities of UUVs deployed to map Q-routes result in higher HVU survival rates
- UUVs that are equipped with neutralization capability provide minimal advantages over localization only UUVs in regards to HVU survival rates
- Average time required to map Q-routes not significantly improved with larger quantities of UUVs

VII. ANALYSIS OF ALTERNATIVES

A. UUV MISSION ALTERNATIVES

UUV alternatives are analyzed in a consistent manner with the project scope, CONOPS and modeling. In order to evaluate the effectiveness of each vehicle or combination of vehicles, an overall effectiveness analysis is conducted with cost as an independent variable (CAIV). A cost effectiveness analysis (Chapter VIII) is factored in to the final evaluation and recommended force structure. The specific configuration of alternatives is based primarily from analysis of the modeling efforts in Chapter VI. Where multiple diameter vehicles are considered, values for the number of vehicles are derived from the point of maximum effectiveness observed in the modeling. For example, in the attack mission area (Chapter VI, Section 4.c) the most effective number of attack gliders is approximately 15, thus 15 gliders are utilized for the analysis of alternatives. This process is used for all modeling and mission areas. The analysis of alternatives matrix (Table 13) details the results of the modeling analysis for determining alternatives for consideration.

Analysis of Alternatives Comparison Matrix				
Vehicle	**MCM**	**ISR**	**IO**	**Attack**
(1) 21" Recoverable UUV	X	X		
(1) 21" Expendable UUV			X	X
(2) 21" Recoverable UUV			X	
(2) 21" Expendable UUV			X	
(4) 21" Recoverable UUV		X		
(4) 21" Expendable UUV		X		X
(6) 21" Recoverable UUV	X			
(6) 21" Expendable UUV	X			
(1) 48" UUV	X	X	X	X
(1) 60" UUV	X	X	X	X
(1) SSN	X	X	X	X
(15) Expendable Gliders				X

Table 13. Analysis of Alternatives Comparison Matrix. Quantity and size of UUVs chosen for the analysis of alternatives are derived from mission modeling data. Combinations that resulted in the maximum mission effectiveness are included for the analysis of alternatives.

The factors that are considered for effectiveness originate in the core capabilities that we identified early in the SEA-19A project life cycle. These enduring capabilities are translated into measures of effectiveness that allow for a comparison among alternatives. These capabilities are expressed in quantitative measures when possible. An attempt is made to limit the injection of qualitative data in the scoring of alternatives. The factors considered in the analysis of alternatives, as well as the definition and data sources are:

- **Mission Effectiveness** – Mission effectiveness is how well the mission is achieved by the particular vehicle or combination of vehicles. This data is derived from the modeling of the missions. This data is unique for each mission area. Mission effectiveness for the attack mission is the mean number of enemy casualties. For IO and MCM the effectiveness is survival of the friendly submarine. In the ISR mission area the values for mission effectiveness are chosen based on probability of mission success, where mission success is defined as the successful recovery and subsequent upload of mission data in the recoverable UUV case and by successful transmission of mission data from a remote location in the expendable UUV case.
- **Endurance** – Endurance is defined from the endurance capability model (Chapter VI, Section C.1) for all vehicles sizes. The total achievable ranges of specific vehicles are compared at a velocity of four knots. The maximum

achievable mission time is a ninety day mission of an attack submarine. This factor is consistent across all mission areas. Table 14 details endurance values.

Endurance (Hours)	
21" UUV	107.62
48" UUV	576.424
60" UUV	704.544
SSN	8640
Glider	430.48

Table 14. Notional UUV Endurance Based on Endurance Capability Model. Notional UUV endurance is determined based of the endurance model located in Chapter VI, Section C.1.

- **Stealth –** Stealth is defined as a factor of volume and mast signature at periscope depth. Volume is a large driver in the visibility of the vehicle when it is at or near the surface. It is also a large factor in the submerged signature of a vehicle when active sonar is employed against the vehicle. Active acoustic return of the vehicle is deemed an appropriate measure as modeling of the passive signature showed nearly zero difference between UUVs of differing dimensions and attack submarines. This factor is consistent across all mission areas.
- **Ease of Tactical Use / Risk to Host Platform –** This factor weighs heavily upon the time required for deployment and recovery of vehicles. Ease of tactical use and risk to host platform are linked factors because the amount of time the host platform is at risk or vulnerable to attack is dependent upon the time it takes to launch or recover a vehicle. With this factor expendable vehicles do not account for the recovery time. This factor is variable among mission areas. Assumed risk times are denoted in Table 15.

Platform At Risk Times (Minutes)	
21" Expendable UUV	2
21" Recoverable UUV	60
48" UUV	60
60" UUV	90
SSN (weapon or decoy launch)	2
SSN (minefield Q-route)	1440
Glider	2

Table 15. Host Platform Vulnerability Duration. Assumed times required to launch or recover UUVs may place platforms at risk, due primarily to being restricted in ability to maneuver and potentially increased acoustic noise levels.

- **Mission Flexibility –** Mission flexibility is a function of the volume of the vehicle. Vehicles of differing diameters are modeled as the same length of vehicle. The mission section is modeled as a ten foot section. An attack submarine is modeled to have the capacity to carry thirty-eight 21” weapons plus twenty-eight more weapons in the proposed Virginia Payload Modules (LaGrone 2011).
- **Years to Field –** The number of years assumed that the alternative will take to be fielded is based on its respective Technology Readiness Level (TRL). The TRL is the maturity of, and the risk associated with, critical technologies to be used in Major Defense Acquisition Programs (MDAPs) (Assistant Secretary of Defense for Research and Engineering 2011).

With the attributes defined, the next step is to assign attribute values for each alternative on a value scale. Within each mission area all alternatives are compared against each other with regard to the attributes. Each attribute value is translated into a value between zero and one. A score of one is the best that any alternative is capable of achieving and a score of zero means that alternative has zero value with respect to the attribute. Once the attribute with the best value is set to one, all other values within that mission area are set as a ratio of the best value. Refer to Appendix F for a full listing of all attribute values and attribute value score tables for all mission areas.

Once the values for each attribute are determined, multi-attribute decision analysis is used to quantitatively compare the alternatives. This decision analysis helps in selecting a recommended alternative with conflicting objectives that were previously mentioned. The multi-attribute decision analysis starts with assigning weights to each

attribute within each mission area. Each mission area must be analyzed separately since the attributes have different levels of importance in each mission area. Swing weighting is used to assign weights to each attribute. A swing weight takes into account the relative importance and variation between the attributes. The first step in assigning swing weights is to create an ordinal scale of the attributes by ranking the importance of each attribute within each mission area. This is done by a team vote and is based on how important each attribute is with respect to the mission area. Table 16 summarizes the rankings of the attributes.

	ISR	MCM	IO	Attack
Mission effectiveness (modeling)	1	1	1	1
Endurance (kWh)	3	3	3	2
Stealth (size - volume)	2	5	5	4
Ease of tactical employment (L/R time, personnel/host platform risk)	5	2	2	5
Years to field (based on TRL)	6	6	6	6
Mission flexibility (available payload volume)	4	4	4	3

Table 16. Mission Attribute Rankings. Each mission area is evaluated separately and the capability attributes from each individual mission are ranked from 1 being the most important, to 6 being the least important.

In order to assign swing weights, a relative importance rating is assigned to each attribute based upon its respective ranking. The highest ranked attribute gets an automatic rating of 100. Each attribute after this is assigned a rating based on its relative value as compared to the highest ranked attribute. The rationale in the highest ranked attribute receiving a rating of 100 is that if that attribute was maximized, it would be the most valuable, or in other words that alternative would have a 100 percent increase in value. For example, if the second ranked attribute is assigned a rating of 75, the translation is that the alternative would increase in value by 75 percent if the second attribute was maximized as compared to the highest ranked attribute. Once all ratings have been assigned, the ratings are normalized in order to sum to one. Table 17 summarizes the attribute weights for each mission area.

ISR Attribute Weighting	**Rank**	**Rate**	**Weight**
Mission effectiveness (modeling)	1	100	0.508
Endurance (kWh)	3	25	0.127
Stealth (size - volume)	2	50	0.254
Ease of tactical employment (L/R time, personnel/host platform risk)	5	6.25	0.032
Years to field (based on TRL)	6	3.125	0.016
Mission flexibility (available payload volume)	4	12.5	0.063
	check sum		1

IO Attribute Weighting	**Rank**	**Rate**	**Weight**
Mission effectiveness (modeling)	1	100	0.508
Endurance (kWh)	3	25	0.127
Stealth (size - volume)	5	6.25	0.032
Ease of tactical employment (L/R time, personnel/host platform risk)	2	50	0.254
Years to field (based on TRL)	6	3.125	0.016
Mission flexibility (available payload volume)	4	12.5	0.063
	check sum		1

MCM Attribute Weighting	**Rank**	**Rate**	**Weight**
Mission effectiveness (modeling)	1	100	0.508
Endurance (kWh)	3	25	0.127
Stealth (size - volume)	5	6.25	0.032
Ease of tactical employment (L/R time, personnel/host platform risk)	2	50	0.254
Years to field (based on TRL)	6	3.125	0.016
Mission flexibility (available payload volume)	4	12.5	0.063
	check sum		1

Offensive Attack Attribute Weighting	**Rank**	**Rate**	**Weight**
Mission effectiveness (modeling)	1	100	0.508
Endurance (kWh)	2	50	0.254
Stealth (size - volume)	3	25	0.127
Ease of tactical employment (L/R time, personnel/host platform risk)	5	6.25	0.032
Years to field (based on TRL)	6	3.125	0.016
Mission flexibility (available payload volume)	4	12.5	0.063
	check sum		1

Table 17. Mission Attribute Weightings. Ratings are assigned to each mission attribute ranking and then normalized for a final weighting.

The next step is to use a mathematical model to calculate the final values to each alternative within each mission area. The mathematical model used is an additive model. The following equation is used to calculate each alternative's value (Parnell 2013):

$$v(x)=\sum_{i=1}^{n} w_i v_i(x_i)$$

where:

$v(x)$ = the alternative's value

$i=1$ to n is the number of the value measure

x_i = the alternative's score on the i^{th} value measure

$v_i(x_i)=$ the single dimensional value of a score x_i

w_i = the weight of the i^{th} value measure

$\sum_{i=1}^{n} w_i = 1$ All weights sum to one

To illustrate these calculations, the single twenty-inch expendable UUV has an "Offensive Attack" overall score of 0.18. The weights of each value measure for Offensive Attack are shown in Table 17. The single dimensional value score for each attribute for this alternative is as follows:

- Mission effectiveness – 0.023
- Endurance – 0.012
- Stealth – 1.0
- Ease of tactical employment – 1.0
- Years to field – 0.333
- Mission flexibility – 0.007

The calculation for the single twenty-inch expendable UUV overall score is shown below.

$$Score = (.508)(.023) + (.254)(.012) + (.127)(1.0)$$
$$+ (.032)(1.0) + (.016)(.333) + (.063)(.007) = .179$$

Table 18 summarizes the overall scores for each alternative within each mission area with the highest scoring alternatives highlighted.

Offensive Attack Alternatives	Score
(1) 21" Expendable UUV	0.18
(1) 48" UUV	0.10
(1) 60" UUV	0.09
(4) 21" Expendable UUVs	0.10
Sub	0.88
(15) Expendable Gliders	0.12

ISR Alternatives	Score
(1) 21" Recoverable UUV	0.53
(1) 48" UUV	0.33
(1) 60" UUV	0.31
(4) 21" Expendable UUVs	0.58
Sub	0.76
(4) 21" Recoverable UUVs	0.63

IO Alternatives	Score
(1) 21" Expendable UUV	0.68
(1) 48" UUV	0.38
(1) 60" UUV	0.38
(2) 21" Recoverable UUVs	0.54
SSN	0.78
(2) 21" Expendable UUVs	0.66

MCM Alternatives	Score
(1) 21" Recoverable UUV	0.17
(1) 48" UUV	0.15
(1) 60" UUV	0.15
(6) 21" Recoverable UUVs	0.42
SSN	0.26
(6) 21" Expendable UUVs	0.46

Table 18. Mission Alternatives Final Scoring (with SUB). As expected the submarine is the most effective platform for all mission sets except MCM.

With the exception of MCM, the submarine alternative scores higher than any alternative, and this was an expected result. For MCM, six 21” expendable UUVs had the highest score, followed closely by six 21” recoverable UUVs. Six 21” UUVs, whether

recoverable or expendable, overwhelm the other alternatives. In the attack, ISR, and IO mission areas, the submarine score overwhelmed most or all of the other alternatives' scores. This creates a concern that the submarine is skewing the value function scores of the other alternatives. The submarine performs better on such a higher magnitude that it makes the other alternatives appear as invaluable when comparing the final scores. A second analysis without submarines included as an alternative is necessary to see how the other alternatives' scores change. The first step in this revised analysis is to assign new value function scores for each attribute of each alternative. With the submarine excluded the scale changes and new ratios are setup to assign each attribute new value scores. Refer to Appendix F for the revised attribute value score tables for all mission areas.

With the revised attribute value scores, the same additive equation is used to calculate new final scores for each alternative. Table 19 summarizes the revised final scores with the highest scoring alternatives highlighted.

Offensive Attack Alternative	Score
(1) 21" Expendable UUV	0.28
(1) 48" UUV	0.56
(1) 60" UUV	0.60
(4) 21" Expendable UUVs	0.40
(15) Expendable Gliders	0.73

ISR Alternative	Score
(1) 21" Recoverable UUV	0.55
(1) 48" UUV	0.46
(1) 60" UUV	0.49
(4) 21" Expendable UUVs	0.61
(4) 21" Recoverable UUVs	0.66

IO Alternative	Score
(1) 21" Expendable UUV	0.71
(1) 48" UUV	0.51
(1) 60" UUV	0.56
(2) 21" Recoverable UUVs	0.69
(2) 21" Expendable UUVs	0.69

MCM Alternative	Score
(1) 21" Recoverable UUV	0.20
(1) 48" UUV	0.28
(1) 60" UUV	0.33
(6) 21" Recoverable UUVs	0.46
(6) 21" Expendable UUVs	0.74

Table 19. Mission Alternatives Final Scoring (without SUB). With the submarine removed, expendable platforms tend to dominate the final scoring for most of the mission areas.

With the submarine alternative removed there is a significant change in the overall scores for each alternative. With the exception of IO, multiple 21” expendable UUVs score significantly better than the other alternatives within each mission area. In the IO mission area, a single 21” UUV scored higher than the other alternatives but by a close margin. The multiple 21” expendable UUVs were very close in score. Another beneficial analysis is to compare the rank of each alternative with submarine included as

an alternative and with the submarine alternative excluded. Table 20 shows the ranks of each alternative within each mission area with the submarine included and excluded.

Offensive Attack Alternative	Rank (with Sub)	Rank (without Sub)
(1) 21" Expendable UUV	2	5
(1) 48" UUV	5	3
(1) 60" UUV	6	2
(4) 21" Expendable UUVs	4	4
Sub	1	
(15) Expendable Gliders	3	1

ISR Alternative	Rank (with Sub)	Rank (without Sub)
(1) 21" Recoverable UUV	4	3
(1) 48" UUV	5	5
(1) 60" UUV	6	4
(4) 21" Expendable UUVs	3	2
Sub	1	
(4) 21" Recoverable UUVs	2	1

IO Alternative	Rank (with Sub)	Rank (without Sub)
(1) 21" Expendable UUV	2	1
(1) 48" UUV	5	5
(1) 60" UUV	6	4
(2) 21" Recoverable UUVs	4	2
SSN	1	
(2) 21" Expendable UUVs	3	3

MCM Alternative	Rank (with Sub)	Rank (without Sub)
(1) 21" Recoverable UUV	4	5
(1) 48" UUV	6	4
(1) 60" UUV	5	3
(6) 21" Recoverable UUVs	2	2
SSN	3	
(6) 21" Expendable UUVs	1	1

Table 20. Final Mission Alternative Rankings. These revised rankings take into account the final scoring observed for each configuration listed in Tables 18 and 19.

In comparing the rankings of the alternatives with and without the submarine alternative, a significant change was not seen in the ranks with the exception of the alternatives for the attack mission. The attack alternative rankings underwent almost a complete rank reversal. This most likely happened due the submarine alternative dominating the other alternatives. The team's consensus is that the attack alternative rankings with the submarine excluded as well as the final attack scores with the submarine excluded provide better results to make a recommendation for a UUV equipped to conduct attack missions.

B. ATTRIBUTE WEIGHTING SENSITIVITY ANALYSIS

When dealing with complex decisions, systems engineer must be cognizant of the robustness of the analysis of alternatives (Driscoll, Henderson, & Parnell 2011). A sensitivity analysis will reveal if a change in an assumption changes the preferred solution. A common method is to analyze the sensitivity of the weighting of the attributes (Driscoll et al. 2011). In the sensitivity analysis, each attribute is analyzed one at a time, within each mission, by changing the attribute weight to one with all other attributed weighted to zero. The same additive equation used to calculate each alternative's overall score is used to recalculate the scores with the revised weights. The original scores and new scores are plotted against the original weights and the revised weights. To determine the sensitivity of each attribute, points of inflection on the plot are compared against the original weights. Specifically, it is the x-coordinate of the points of inflection that are of concern. The project team used a rule of thumb that if a point of inflection is within 0.1 of the original weight, the alternative scores are sensitive to that weight. Table 21 summarizes the results of the sensitivity analysis. In the columns labeled new weight, the number shown is the weighting of the attribute where a point of inflection is seen. A point of inflection is where an alternative preference changes. In the analysis of each attribute, there are usually several points of inflection. Table 21 shows the closest weight to the original weight where a point of inflection is seen.

	Offensive Attack (Original Weight)	Offensive Attack (New Weight)	ISR (Original Weight)	ISR (New Weight)
Mission effectiveness	0.508	0.329	0.508	0.403
Endurance	0.254	0.438	0.127	0.186
Stealth	0.127	0.248	0.254	0.198
Ease of tactical employment	0.032	0.166	0.032	0.132
Years to field	0.016	0.593	0.016	0.118
Mission flexibility	0.063	0.342	0.063	0.123

	IO (Original Weight)	IO (New Weight)	MCM (Original Weight)	MCM (New Weight)
Mission effectiveness	0.508	0.536	0.508	0.361
Endurance	0.127	0.248	0.127	0.241
Stealth	0.032	0.003	0.032	0.123
Ease of tactical employment	0.254	0.232	0.254	0.865
Years to field	0.016	1.000	0.016	0.158
Mission flexibility	0.063	0.188	0.063	0.221

Table 21. Attribute Weighting Sensitivity Analysis. The weights in the gray shaded columns show the weight where the nearest point of inflection to the original weight is observed. Weights highlighted in yellow are those that are within 0.1 of the original weight.

In Table 21, the highlighted weights are those that were within 0.1 of the original weight where a change in preference of the alternatives is seen. It is useful to analyze the plot of weight vs. scores to gain further insight into the sensitivity of this attribute. Figure 52 shows the plot of weight vs. scores for the endurance attribute for ISR.

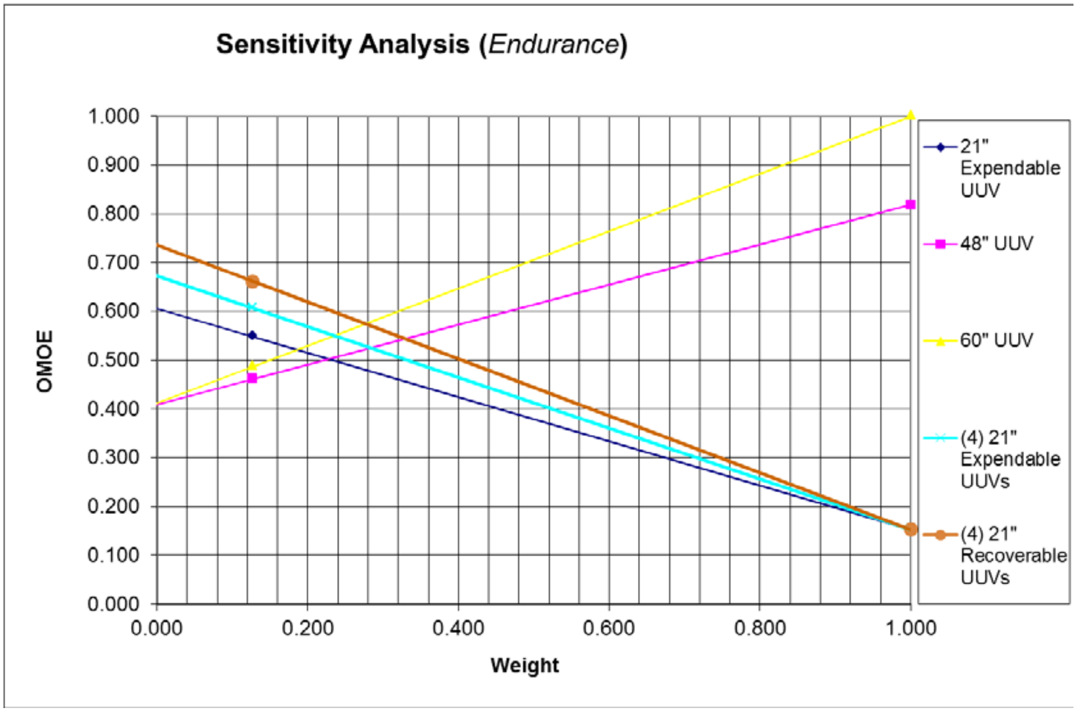


Figure 52. Endurance Sensitivity Plot (ISR). The sensitivity plot shows how the alternative scores change as a result of changing the weighting of the endurance attribute. If the weighting of the endurance attribute is changed to approximately 0.28 from the original weight of 0.127, a 60 inch UUV becomes the highest scoring alternative.

The closest point of inflection for the endurance attribute for ISR is 0.186, with the original weight being 0.127. At this point, a 60 inch UUV is now scored higher than four 21-inch expendable UUVs. However, at this weight four 21-inch recoverable UUVs are still the highest scoring alternative. The weighting would have to change to approximately 0.28 before the highest scoring alternative changes, which would be the 60 inch UUV in this case. This makes sense as the 60 inch UUV has a higher endurance capability than the other alternatives, and if the weighting of endurance is increased, we would expect the scores of the vehicles with higher endurance to increase. The analysis of the other attributes highlighted in Table 21 for ISR is similar to the analysis of endurance. One other attribute that drew attention to the project team was mission effectiveness for IO. If the weighting is changed from 0.508 to 0.536, the preferred solution will change. It is useful again here to analyze the plot of weightings vs. scores for mission effectiveness of IO. Figure 53 shows this plot.

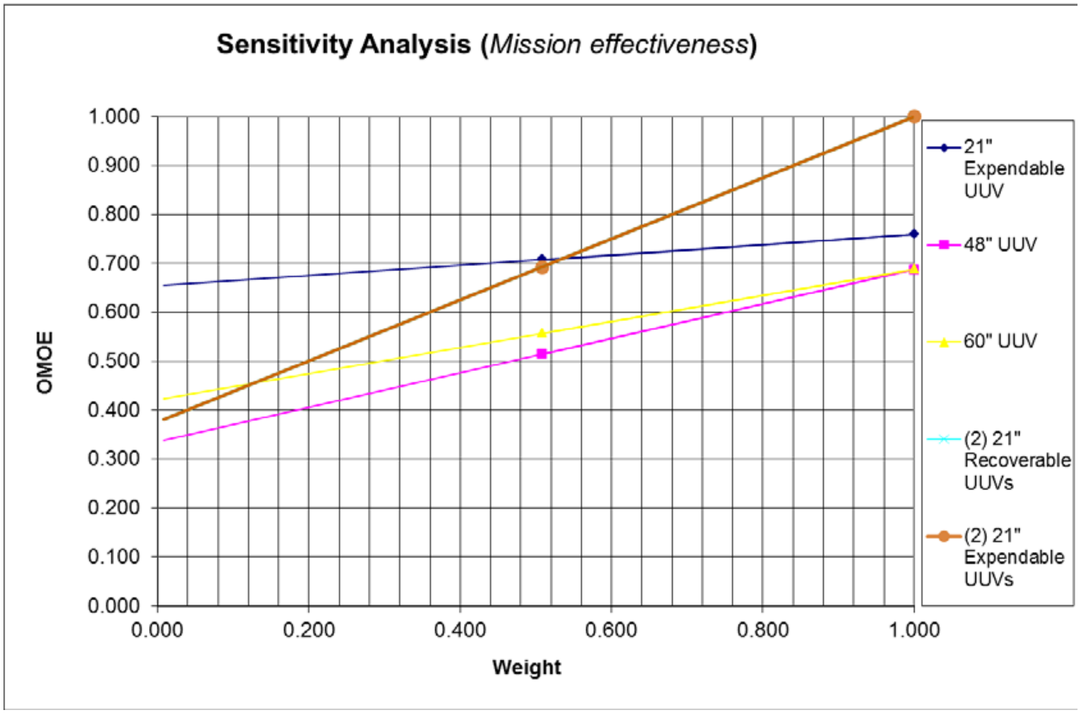


Figure 53. Mission Effectiveness Sensitivity Plot (IO). This sensitivity plot shows how the alternative scores change for IO as a result of changing the original weighting for the mission effectiveness attribute. The highest scoring alternative changes with a slight shift of the weighting due to the fact that the single and two 21-inch UUV alternative had almost the same performance.

At a weighting of 0.536, two 21-inch expendable UUVs score higher than a single 21-inch expendable UUV. There are two explanations for this occurrence. One is that the performance of these two alternatives was almost exactly the same in the modeling and simulation of IO. Additionally, the modeling output of IO revealed there was little statistical significance in the difference between these two alternatives.

When the preferred solution changes as the weighting is varied, this information needs to be reported to key stakeholders and decision makers for resolution (Driscoll et al. 2011). The project team has highlighted which attributes are sensitive to the solutions; however the project team did not have much disagreement in the original weightings of the attributes. Therefore, the project feels confident in the results in the analysis of alternatives. Sensitivity plots for all attributes in each mission are located in Appendix F, section B.

Chapter Summary

In regards to offensive attack operations, the LDUUVs provide the most significant capability. Glider mines also show significant promise but also pose significant issues in regards to legality since they may be viewed as floating mines. This concept will require further analysis before being included in the proposed force structure.

Conducting covert Q-route mapping with multiple UUVs greatly increases submarine and HVU survivability. Use of advanced UUV decoys also shows significant promise of improving submarine survivability.

All mission sets can benefit from operations with 21” UUV variants. LDUUV variants should have missions primarily focused on offensive operations and persistent ISR. Finally, both the IO and attack 21” UUVs have no requirement for recoverability so cost savings can be realized by designing them specifically for expendability. The next chapter specifically focuses on cost estimation of all variants.

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VIII. COST ANALYSIS

A. COST ESTIMATION METHOD

How much is it going to cost? This is one of the most frequently asked questions in regards to concept generation. In an era of rising costs and limited budgets, controlling expenditures and attempting to accurately predict the total taxpayer bill for a proposed system is a necessary endeavor. It is necessary to "abandon inefficient practices accumulated in a period of budget growth and learn to manage defense dollars that is respectful of the American taxpayer, at a time of economic and fiscal distress" (Carter 2010). A strong cost estimation and analysis effort provides key input to the decision making body. Placed side by side with the analysis of alternatives (AoA) in Chapter VII, a system's life cycle cost estimate (LCCE) can help decision makers decide which alternatives considered provide the best cost versus benefit ratios. This cost estimation process is "the art of approximating the probable worth, extent, or character of a system based on information available at the time" (Nussbaum 2013). Figure 54 outlines several benefits of quality cost estimation practices.

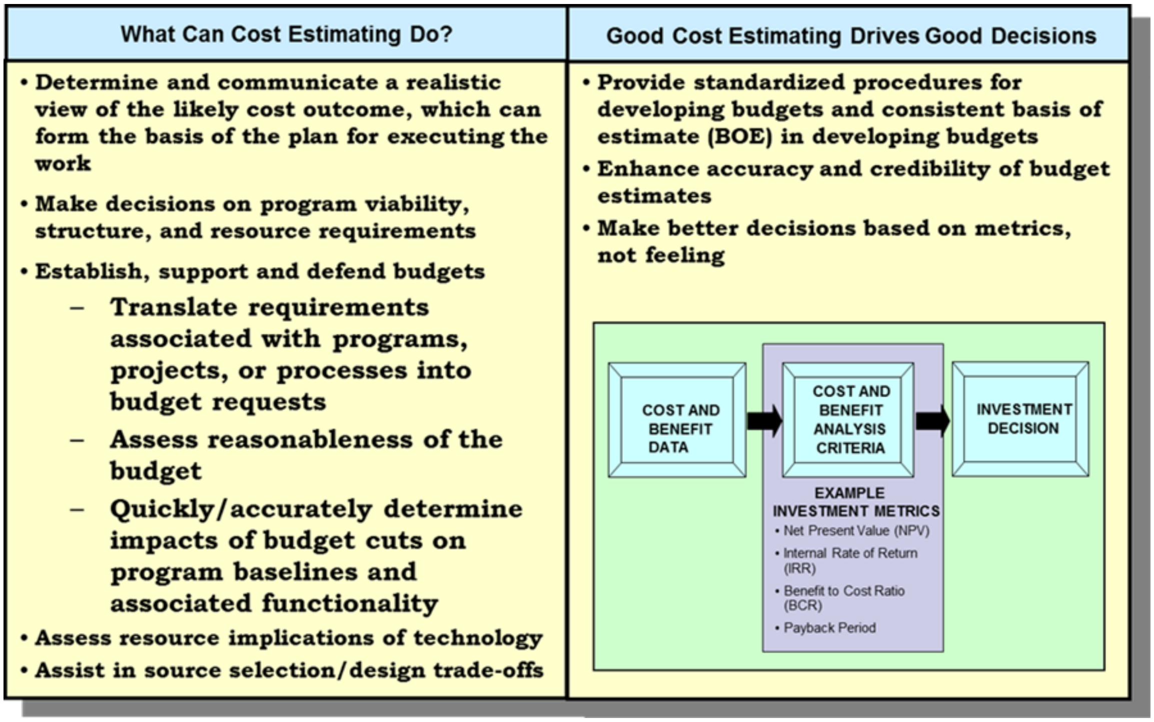

Figure 54. Cost Estimation Principles (From Nussbaum 2013). Effort is given to provide educated decisions based on metrics and historical data, rather than gut feelings. These concepts are especially helpful when conducting trade-offs between system performance, cost, and schedule.

Cost estimation is conducted in order to provide input for the AoA and to provide additional insights necessary for the implementation of the proposed notional force structure in Chapter IX. SEA-19A’s cost estimation efforts are intended to generate a reasonable LCCE within the constraints of the problem definition, in order to compare the benefits of each proposed solution to the associated program costs. These estimates are not intended to provide precise cost numbers for specific UUV systems, but instead are used to express an approximate order of magnitude of program costs, from which to analyze various alternatives.

The top-down cost estimating approach is preferred since it allows for a high level of cost aggregation, where costs are statistically derived. This method emphasizes the use of cost driving factors such as mission capability, range, reliability, and other critical attributes (Michaels 1989). This approach also incorporates several quantitative analysis techniques such as data collection, regression analysis, learning curves, and risk analysis.

B. COST ESTIMATION ASSUMPTIONS

Each phase of the project life cycle requires certain assumptions to accurately predict costs. For example, assumptions made in order to determine procurement costs are not necessarily applicable to the assumptions used for research and development cost estimations. Specific cost assumptions regarding each phase of the system life cycle are explained in greater detail in each individual cost estimation section. General assumptions include:

- All dollar amounts are expressed in fiscal year 2013 dollars.
- Where applicable, Joint Inflation Indices provided by the Naval Center for Cost Analysis (NCCA) are utilized.
- Disposal costs are deemed to be constant for all alternatives and are determined by cost per pound.
- UUVs proposed are assumed to be available for fleet use by 2020.
- Six prototype units of each variant will be required for test and evaluation purposes.
- Launch and recovery costs associated with UUV host platforms are not considered.
- 98% learning curves will be applied from the first unit production to the last vehicle produced.
- Operations and Support (O&S) and Procurement costs factor in replacement costs due to the assumed operational loss of one UUV every two years, or 2.5% of active units due to unforeseen circumstances. This assumption corresponds to a similar assumption used by the LDUUV program.

C. COST ESTIMATION DATA ANALYSIS

UUV cost data collection and cost estimations are challenging since there are not many DoD UUV Programs of Record to draw historical data from. Even though there have been several developmental programs over the past 30 years, very few UUVs have progressed to operational stages of development. The majority of cost data is derived from programs the U.S. Navy has funded or is currently funding to include, UUVs, undersea weapons, SEAL delivery vehicles (SDVs/ASDS), and training systems that are comparable to proposed UUVs in size and structure. UUV cost data is also obtained from naval enterprise stakeholders for commercially available UUV systems of similar size

and capabilities. Historical data regarding replacement parts, sensor technologies, batteries, and power consumption costs are also used to aid in cost estimation.

Significant effort is made to capture as many of the UUV life-cycle costs (LCC) as possible to develop realistic program cost estimates. The complexities involved in estimating the cost of conceptual systems which are not yet in development do not favor a detailed and accurate analysis of LCC; however, a cost estimation analysis is required to be able to choose between alternative solutions by way of an objective cost-benefit analysis (Nussbaum 2013). The remainder of this chapter analyzes the components related to UUV LCC estimates, which are very similar to typical LCC components of major DoD acquisition programs shown in Figure 55.

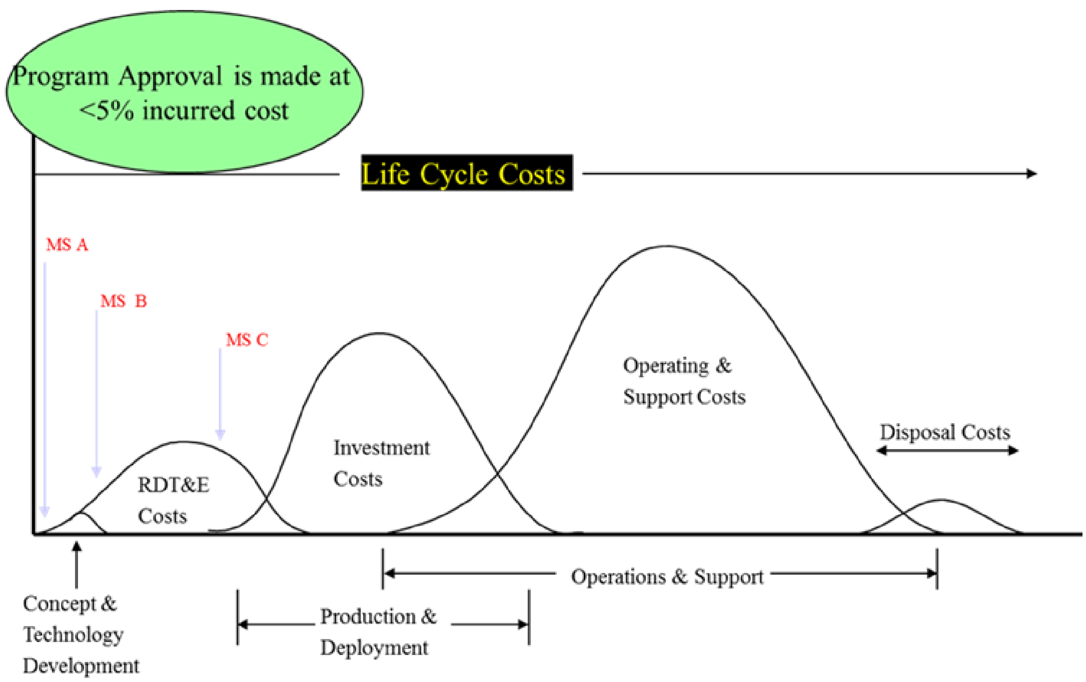

Figure 55. Typical Life Cycle Cost (LCC) Structure (From Michaels 1989). Operations & Support costs generally constitute the largest percentage of LCC. Program approval decisions however, are generally made with as little as 5% of the total cost invested. Attempts are made to capture as many of the total LCCs as possible to prevent significant cost overruns.

1. Procurement Costs

Initial cost modeling efforts focus on procurement costs, due to the fact that the remaining phases of LCC are derived from the procurement cost when a system is still in a relatively nascent stage such as UUVs. Procurement costs are alternatively known as investment cost or construction cost. The *Defense Acquisition Guidebook* (DAG) specifically defines investment cost as “production and deployment costs incurred from the beginning of low rate initial production through completion of deployment” (DAG 2012).

Linear regression models and adjusted inflation curves are used in conjunction with current and historical data to develop the cost estimation model. Cost data collection initially focused on commercially produced UUVs that are similar in size and capability to the UUVs envisioned in the 2024 UUV CONOPS (Chapter V). Due to the proprietary nature of commercial development data, civilian manufacturers were reluctant to provide their cost data in detail, or even at all. The lack of actual UUV data required the team to look at other platforms that perform similar functions.

Analogous systems such as torpedoes and training targets are used to increase the data available to produce realistic cost estimates. In many ways, self-propelled torpedoes can be considered UUVs (Whitman 2002). The MK 46 Mod 5, MK 48 Mod 7 ADCAP, MK 50, and MK 54 LWT torpedo cost data is obtained from the Defense Cost and Resource Center (DCARC). Cost data for ASW training targets such as the MK 30 Mod 2 is also used since the technology, size, and function of the vehicles are the similar to a basic UUV. Contract data is also readily available for these systems (Defense Industry Daily Staff 2007).

Vehicle	Weight (lb)	FY13$K	Source
9"- UUV	134	562	Manufacture Data
12.5" A-UUV	470	995	Manufacture Data
12.5" B-UUV	530	1401	Manufacture Data
12.5" C-Torp	508	286	DCARC
12.5" D- Torp	800	546	DCARC
12.5"E- Torp	608	1250	DCARC
21" A- UUV	2780	2757	NUWC NPTASW AOA
21" B- UUV	2742	2961	DCARC
21" C- UUV	1650	2553	Manufacture Data
21" D- Torp	3695	3032	DCARC
48" A- UUV	14000	11952	RMS SAR
60" A-UUV	8240	8168	Manufacture Data

Table 22. Collected Historical Cost Data. Historical UUV and torpedo cost data is obtained from manufacturers, DCARC and other applicable sources. Data is analyzed to provide evidence based cost estimates of proposed systems.

Several variations of physical and performance characteristics of the set of vehicles are analyzed in contrast to cost in FY13 dollars, to include: length, diameter, weight, range, sensors, endurance, payload, and propulsion characteristics. Analysis reveals that the single most conclusive cost driver for UUVs is weight out of the water. Cost data analyses of current UUV programs, future UUV budget proposals, and torpedoes show that the cost versus weight relationships have held fairly constant through different platforms and technologies.

Weight versus cost data is plotted in Figure 56, resulting in a fairly linear trend line that produces the following cost estimating relationship (CER):

Cost (FY13$K) = 0.842 (Weight in Pounds) + 501.7

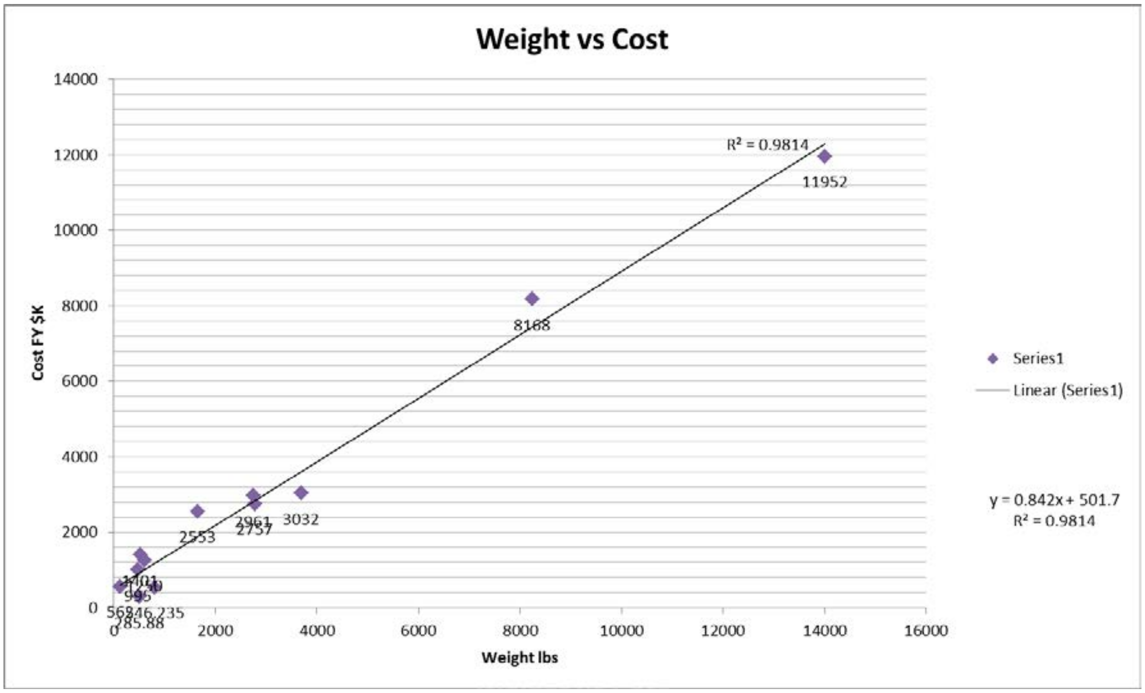

Figure 56. Weight vs. Cost Plot in FY13 Dollars. Very few UUVs or analogous systems over 4000 lbs have ever been produced, which makes it difficult to confirm linear relationships in the upper range. However, based on available data, weight vs. cost provides an adequate tool for UUV cost estimation purposes.

In order to apply the CER, reasonable assumptions for the weights of each subset of vehicles are required. The weight approximation for the 21” diameter vehicles is calculated by taking the average of the weights of all the 21” variants. Then an expendable 21” vehicle’s weight is reduced by 300 pounds and a 21” recoverable vehicle is increased by 300 pounds to account for the assumed weight differences. The weight for the 60” variants are determined based on the known weights of commercially available 60” vehicles plus the expected weight of additional items such as sensors, batteries, and mission-specific equipment. The weight of the 48” variant is extrapolated directly from the diameter vs. weight trend line. This is due to the fact that the only 48” vehicle currently available is the diesel Remote Minehunting System (RMS), which is much heavier than other UUV designs of similar magnitude. Figure 57 illustrates the derived diameter vs. weight trend for the entire range of proposed UUV vehicle sizes.

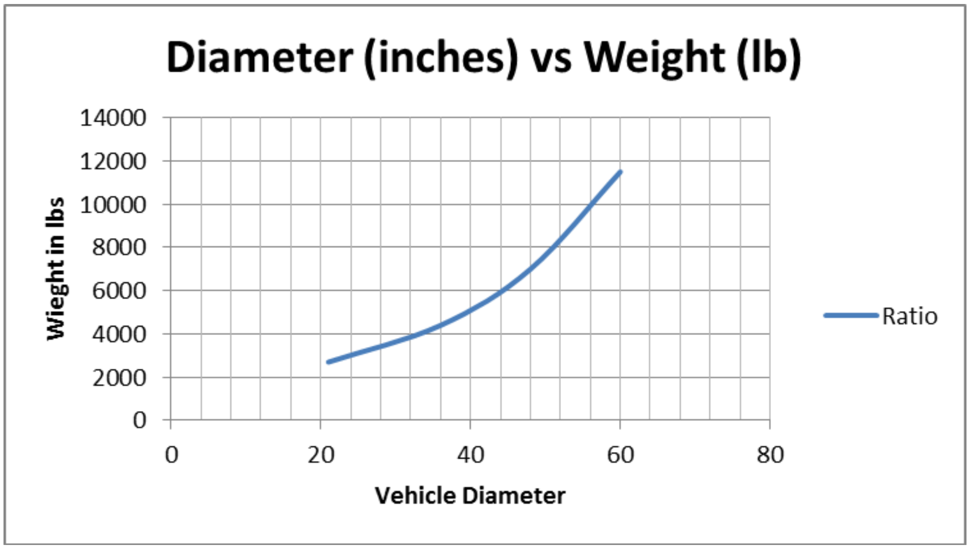

Figure 57. Diameter vs. Weight Plot. The trend exhibits a slightly exponential curve. Increases in vehicle diameter result in significantly higher total vehicle weights.

The final first unit procurement values (Table 23) are calculated based on the predicted weight vs. cost CER equation (Figure 56), using the UUV weights determined in the vehicle diameter vs. weight analysis.

	Glider	21" Expendable	21" Recoverable	48" Recoverable	60" Recoverable
Weight (lbs)	115	2417	3017	7000	10500
Cost FY13$	$ 75,000.00	$ 2,536,603.50	$ 3,143,072.75	$ 6,779,780.00	$ 9,975,280.00

Table 23. First Unit Procurement Costs per UUV Variant in FY13 Dollars. Procurement costs are determined using the baseline cost estimating relationship (CER) of weight vs. cost – [Cost (FY13$K) = 0.842 (Weight in Pounds) + 501.7].

An issue of concern with the initial procurement costs is the 48" and 60" outliers. There is only one data point for 60" vehicles for comparison and none for a 48" variant. Sensitivity analysis is completed to investigate if the outliers may be significantly altering the resultant baseline CER. This is accomplished by completing three additional analyses: the first without the 48" variant, the second without the 60" variant, and finally an analysis without both the 48" and 60" variants. Costs returned in these analyses are then compared to that of the base model as shown in Table 23.

	21" Expendable	21" Recoverable	48" Recoverable	60" Recoverable
All data	$ 2,536,603.50	$ 3,143,072.75	$ 6,779,780.00	$ 9,975,280.00
No 48" or 60"	$ 2,443,199.10	$ 2,916,719.10	$ 6,060,300.00	$ 8,822,500.00
No 60"	$ 2,473,544.65	$ 2,963,024.65	$ 6,212,560.00	$ 9,067,860.00
No 48"	$ 2,595,756.10	$ 3,143,676.10	$ 6,781,180.00	$ 9,977,380.00
No 48" or 60"	-4%	-7%	-11%	-12%
No 60"	-2%	-6%	-8%	-9%
No 48"	2%	0%	0%	0%

Table 24. Procurement Cost Sensitivity Analysis in FY13 Dollars. Data shows that baseline CER model provides conservative cost estimates for UUV variants. Removal of the 48" variant is the only case that resulted is slightly higher cost estimates compared to the baseline CER model. Sensitivity analysis is completed to ensure that limited input data for the LDUUV variants is not manipulating the baseline CER model.

Results of the sensitivity analysis illustrated in Table 24 show that our baseline CER provides conservative cost estimates in all cases, with the exception of the 48" data where the removal produced slightly higher cost estimates. This analysis shows that our baseline CER is not significantly affected by the outlying data points and that it provides a satisfactory model for procurement cost estimation.

Procurement costs of glider UUVs are also calculated. Point estimates are used for the glider data to provide more accurate estimates based on the relatively low costs of the gliders and the high number of commercially available variants (Button 2009). To be conservative, the point estimate for the glider is assumed to be slightly higher than the most expensive glider at $75,000.00 in FY13 dollars. Data from glider programs of record are included for comparison in Table 25.

	Length (in)	Diameter (in)	Weight(lb)	Range (nm)	Duration (days)	Refueling Cost	Cost
Spray Glider	79.2	7.9	112	3780	330	$ 3,549.68	$ 31,137.50
Slocum Glider	58.8	8.3	115	810	20	$ 996.40	$ 62,275.00
Seaglider	70.8	11.8	115	2430	200	$ 1,712.56	$ 74,730.00

Table 25. Glider Cost Data in FY13 Dollars. Considering that modifications may need to be made to gliders to meet scoped missions, the procurement cost has been assumed to be slightly higher that the most expensive glider and point estimated at $75,000.

2. RDT&E Costs

Research, Development, Testing and Evaluation (RDT&E) costs are developmental costs incurred by parties involved in the acquisition of a particular system (both Government and Contractor) over the course of the Material Solution Analysis and Engineering and Manufacturing development phases of the acquisition process (DAG 2012). Typical estimating techniques for this type of cost are normally very robust and involved. The majority of prospective UUV systems are still in various stages of RDT&E and as a result historical cost data in regards to development is not readily available. Instead of relying on raw historical RDT&E cost data, cost estimations are primarily based on historical percentages of RDT&E data (Table 25) obtained from the Naval Center for Cost Analysis, using data for missile weapon systems (Noreen and Bryan 1992). In regards to RDT&E, it is assumed that missile systems are analogous to UUV systems due to similar form factors, technological requirements, and the relatively large number of systems being procured.

Hardware costs are assumed to be the cost of prototypes procured. It is also assumed that the first prototype will cost twice that of the first unit procurement and that six prototypes are acquired for each vehicle size. For the total hardware cost, a 98% learning curve is applied to the cost of the first prototype. For each UUV system, the total hardware cost is assumed to be 23.4% (as shown in Table 26) of total development cost (Nussbaum 2013). All other percentages are estimated based on missile system RDT&E costs.

RDT&E Historical Data	Mean	Std Dev
Design	25.4%	11.4
Hardware (Protypes)	23.4%	10.3
Software	3.1%	4.6
Support	44.1%	10.4
Misc	4.0%	5.3

Table 26. RDT&E Historical Cost Percentages. UUV hardware percentages are derived from first unit procurement costs, prototype costs, and learning curves. All other percentages are estimated based on missile system RDT&E costs (Noreen and Bryan 1992).

Table 27 contains the RDT&E cost breakdown for each UUV variant analyzed. It should be noted that software cost is an artifact of the historical data. Current software costs have the potential to draw a greater percentage of total costs; however for the level of granularity required, the remaining percentages capture sufficient expectations for RDT&E costs.

	Glider	21" Expendable	21" Recoverable	48" Recoverable	60" Recoverable
Design	$ 901,694	$ 30,496,527	$ 37,787,854	$ 76,022,160	$ 112,245,002
Hardware (Protypes)	$ 830,694	$ 28,095,226	$ 34,812,432	$ 70,036,164	$ 103,406,813
Software	$ 110,049	$ 3,722,017	$ 4,611,903	$ 9,278,295	$ 13,699,193
Support	$ 1,565,539	$ 52,948,694	$ 65,608,046	$ 131,991,231	$ 194,882,070
Misc	$ 141,999	$ 4,802,603	$ 5,950,843	$ 11,971,994	$ 17,676,378
Total	$ 3,549,975	$ 120,065,066	$ 148,771,078	$ 299,299,844	$ 441,909,455
Corrected Total	$ 1,817,587	$ 89,568,539	$ 76,170,792	$ 275,397,394	$ 405,136,455

Table 27. RDT&E Cost Breakdown per UUV Variant in FY13 Dollars. Hardware costs are derived from first unit procurement costs, prototype costs, and learning curves. All other costs are generated based on percentages in relation to hardware costs. The corrected total accounts for sunk costs that have already been expended on UUV programs.

3. Energy Cost

Energy constitutes a significant portion of UUV Operation and Support (O&S) costs. Johns Hopkins APL recently conducted a study of lifetime cost of various power options for a notional 54" diameter UUV. Results are shown in Table 28 (Benedict 2012).

LIFE TIME BATTERY POWER COST			
Type	Li-Ion	Ag-Zn	Alkaline
Description	Sat VL 52E cells	BST HIGO DC Cells	Duracells
FY13 High	$ 4,136.07	$ 10,383.57	$ 2,261.52
FY 13 Low	$ 2,594.03	$ 8,691.11	$ 680.93
Lifespan	5 Years	1 Year	NA
Lifetime Cost per Vehicle Low/ High	$ 4,594,500.00	$ 10,414,200.00	$ 2,246,200.00
	$ 2,552,500.00	$ 8,678,500.00	$ 714,700.00

Table 28. Johns Hopkins APL 54" UUV Lifetime Energy Cost Alternatives in FY13 Dollars (From Benedict 2012). Lithium-Ion, Silver-Zinc, and Alkaline battery types are all analyzed for cost effectiveness.

Johns Hopkins APL battery cost data is assumed to be sufficient for cost estimation purposes. Using the endurance capability model (Chapter VI, C.1), required power for each hull is plotted to extrapolate the predicted cost for each power option for all UUV variants. Energy cost trends are captured in Figure 58 and extrapolated energy cost estimates are included in Table 29.

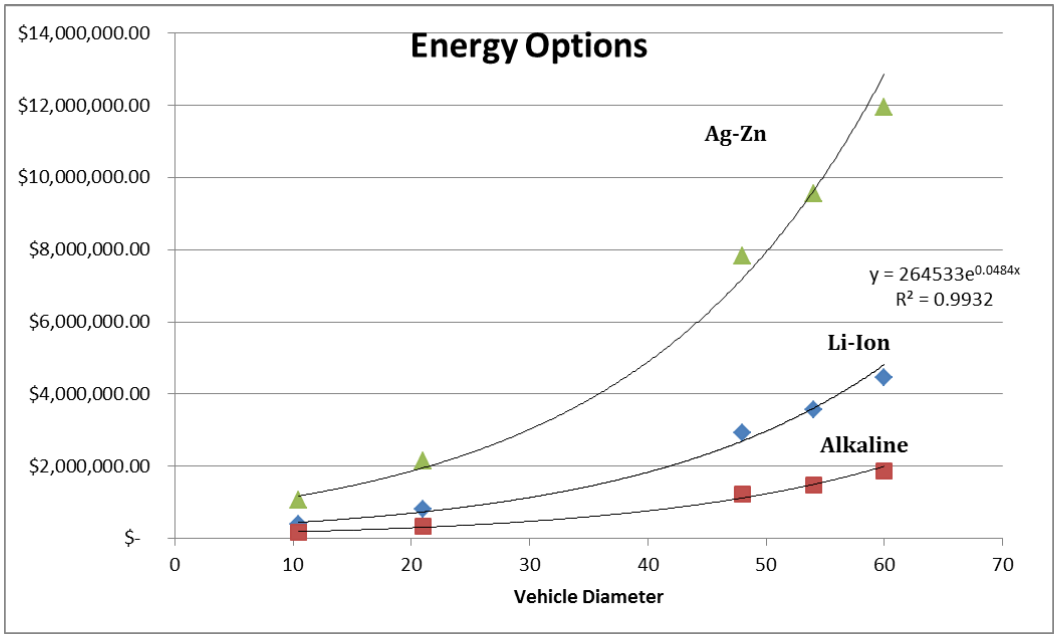

Figure 58. Energy Cost in FY13 Dollars versus UUV Size. The endurance capability model (Chapter VI, C.1) is utilized with input data derived from the power source alternatives analysis from Johns Hopkins APL. Cost estimates are then extrapolated from the trends lines to estimate energy costs for applicable UUV variants.

Diameter	Li-Ion	Alkaline	Ag-Zn
Glider	$ 400,829.85	$ 166,058.08	$ 1,070,788.31
21	$ 801,659.70	$ 332,116.16	$ 2,141,576.62
48	$ 2,934,889.73	$ 1,215,882.89	$ 7,840,348.29
54	$ 3,573,500.00	$ 1,480,450.00	$ 9,546,350.00
60	$ 4,470,271.86	$ 1,851,969.77	$ 11,942,011.98

Table 29. Lifetime Energy Cost per UUV Variant in FY13 Dollars. Energy cost estimates are extrapolated from Figure 58.

4. O&S Costs

The Visibility and Management of Operating and Support Costs (VAMOSC) program is the most complete source of Operating and Support (O&S) cost data currently available. VAMOSC is utilized to determine the O&S costs of various weapon systems and sensors to determine the key factors for deriving reoccurring annual O&S costs. Energy costs are derived in Section C.3. Replacement cost estimates assume that one non-expendable UUV would be lost every two years, an expendable UUV would be lost every five years (aside from those expended for mission and training) and one glider would be lost every three months. Long-Term Mine Reconnaissance System (LMRS) and ASW expendable training unit data from VAMOSC are analyzed to determine a maintenance cost per year. Maintenance costs are assumed to be approximately 7% of procurement cost for the recoverable units and 2% for expendable units. Software costs are assumed to be approximately 2% of procurement cost per year based on the LMRS data.

Table 30 includes the cost estimates for critical O&S factors related to UUV operations.

	O&S Glider	21" Expendable	21" Recoverable	48" Recoverable	60" Recoverable
Maintenance	$ 2,250.00	$ 50,732.07	$ 220,015.09	$ 474,584.60	$ 698,269.60
Software	$ 7,500.00	$ 76,098.11	$ 94,292.18	$ 203,393.40	$ 299,258.40
Energy Cost	$ 3,549.68	$ 5,535.27	$ 40,082.98	$ 146,744.49	$ 223,513.59
Replacement	$ 1,875.00	$ 12,683.02	$ 78,576.82	$ 169,494.50	$ 249,382.00
Recovery	$ 1,500.00	$ 6,341.51	$ 62,861.46	$ 135,595.60	$ 199,505.60
Total	$ 16,674.68	$ 151,389.97	$ 495,828.53	$ 1,129,812.59	$ 1,669,929.19

Table 30. O&S Cost Breakdown per UUV Variant in FY13 Dollars. Percentage and actual cost based approaches are used to derive O&S cost estimates, based primarily on VAMOSC data, manufacturer data, and critical analysis.

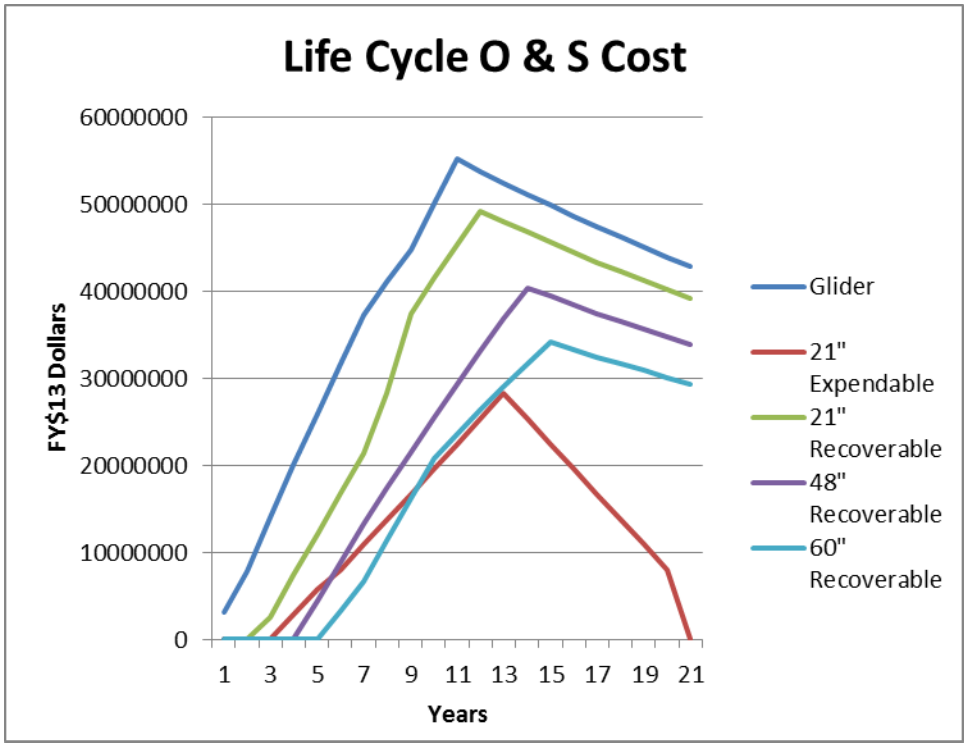

Figure 59. O&S Cost by Year per UUV Variant in FY13 Dollars. Costs are assumed to follow typical O&S trends. Program mid-life is expected to have the highest O&S costs due to the maximum number of operational UUVs still in service. As UUVs are expended or retired, O&S costs are expected to fall.

In Figure 59, O&S costs rise over the first ten years of the program as units continue to be placed into service and then fall off as the older units are retired or expended. This is a typical trend of weapon systems and it is assumed that UUV systems will follow a similar trend. The analysis of O&S costs showed that using a function of production units cost per year is more consistent than evaluating O&S costs on a per deployment basis.

5. Disposal Costs

Disposal costs, while overall a very small section of the total life-cycle cost, are nonetheless an important cost to consider, especially when comparing recoverable units to expendable ones. Cost per pound is a frequently used method for accounting for disposal costs. Analysis of historical VAMOSC data resulted in an estimate of $5 per pound. This data is then combined with the weight of the vehicles to give a final disposal cost. The only exceptions are the expendable variants, of which only 20% at most are

expected to remain in inventory at program termination and require disposal; therefore a cost of $1 per pound is utilized for expendable variants. Table 31 summarizes the total disposal cost estimations for all UUV variants.

	Glider	21" Expendable	21" Recoverable	48" Recoverable	60" Recoverable	Cost/per Pound
Disposal Cost per Unit	$ 575.00	$ 2,416.75	$ 15,083.75	$ 35,000.00	$ 52,500.00	$5

Table 31. Disposal Cost Breakdown per UUV Variant in FY13 Dollars. Costs are based on UUV weight and cost per pound. Disposal costs for recoverable units are $5 per pound and expendable units are $1 per pound.

D. LCCE FOR ALTERNATIVES

Life cycle cost estimation (LCCE) for all of vehicle sizes is first determined by combining the LCC elements derived in Section C, which include RDT&E, Procurement, O&S and Disposal.

FY13$	Glider	21" Expendable	21" Recoverable	48" Recoverable	60" Recoverable
RDT&E Per Unit	$ 454	$ 248,801	$ 662,355	$ 6,884,935	$ 17,614,628
PROCUREMENT Per Unit	$ 58,089.67	$ 2,093,872	$ 2,362,168	$ 5,494,511	$ 8,573,001.72
O&S Per Unit	$333,493.50	$ 3,027,799	$ 9,916,571	$ 22,596,252	$ 33,398,583.86
DISPOSAL Per Unit	$ 575.00	$ 2,416.75	$ 15,083.75	$ 35,000.00	$ 52,500.00
LCC Per Unit	$ 392,613	$ 5,372,889	$ 12,956,177	$ 35,010,698	$ 59,638,714

Table 32. Per Unit Life-Cycle Costs in FY13 Dollars. This provides a per unit consolidation of the life-cycle costs derived in Section C.

Figure 60 illustrates that as size and capability increase, the life cycle per unit cost also increases drastically. Additionally, it shows that the O&S costs are the most significant cost driver of all life-cycle phases, which corresponds to historical cost distributions from analogous systems.

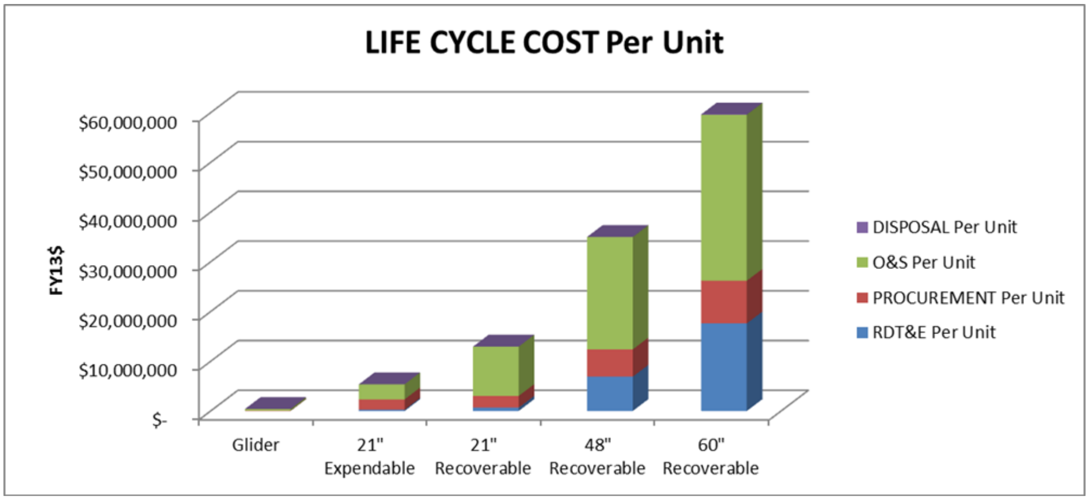

Figure 60. Per Unit Life Cycle Costs in FY13 Dollars. This figure provides a graphical representation of the information in Table 31. This shows the weight vs. cost relationship and the significant portion of cost related to O&S.

1. Overall Acquisition Program LCCE

Although per unit life-cycle cost provides valuable information, it leaves out many factors in the acquisition cycle that affect life cycle costs. Per unit cost estimates disregard critical factors such as the cost savings realized by purchasing large quantities of vehicles. Based on modeling efforts and the AoA, many smaller less capable UUVs would need to be purchased to provide the similar mission effectiveness as larger more capable units. To provide cost correction, acquisition program LCCE methods use the actual predicted cost of each unit based on a learning curve. The assumed acquisition program looks at each vehicle's life cycle from fiscal year 2014 to fiscal year 2034.

Proposed UUV programs all have different estimated RDT&E phase completion timelines that correspond to the first production vehicle available for fleet use. Estimated RTD&E times are:

- Glider: 1 year
- 21" Expendable: 4 years
- 21" Recoverable: 3 years
- 48" Recoverable: 5 years
- 60" Recoverable: 5 years

The primary factor evaluated is the per-year build for each vehicle. It is assumed that the total system purchase price is spread over a ten year period from the start of production. The Operations and Support costs are determined per year, for each vehicle that is in operation, multiplied by the estimated O&S per vehicle cost. The number of in-operation vehicles is determined by summing the new production units placed in service and units already in an operational status. Expected vehicle loss rates are then subtracted from this total. UUV loss rates are assumed to be 20 vehicles per year for the expendable 21" units and one vehicle every two years or 2.5% of operating units for recoverable UUVs.

FY13$K	Glider (4,000)	21" Expendable (360)	21" Recoverable (115)	48" Recoverable (40)	60" Recoverable (23)
RDT&E Total	1,817.6	89,568.5	76,170.8	275,397.4	405,136.5
PROCUREMENT LC	175,388.1	638,940.3	276,270.1	226,739.6	202,572.1
O&S Total	812,821.7	270,515.4	653,118.2	486,916.2	390,986.5
DISPOSAL total	1,547.5	84.6	1,192.3	1,049.1	923.3
Total program LCC	991,574.8	999,108.8	1,006,751.4	990,102.3	999,618.3
Number of Units	4000	360	115	40	23

Table 33. Acquisition Program Life-cycle Costs in FY13K Dollars. All UUV variants are assumed to have one billion FY2013 dollars available for the total acquisition program LCCE. Intention is to investigate how many units of each variant can be purchased given a reasonable cost constraint.

The acquisition program LCCE model is used to determine the maximum amount of units that can be acquired when constrained by a total program budget of one billion FY2013 dollars for each UUV variant, as shown in Table 33. This approach is useful in illustrating the different forces structures available, given a reasonable cost constraint.

Figure 61 provides visualization of the data in Table 33 and highlights the relative differences in O&S and procurement commitments for the UUV variants analyzed.

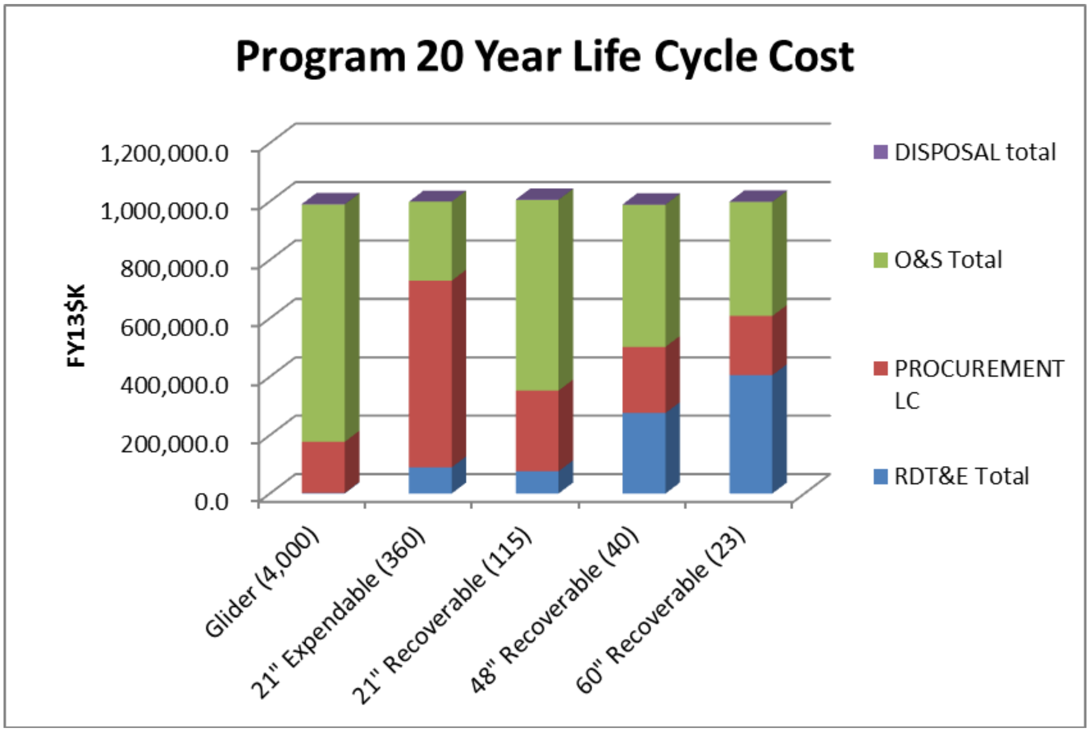

Figure 61. Platform Life-cycle Cost Given One Billion FY13 Dollar Cost Constraint. This provides an approximate breakdown of LCCs given a specific budget constraint or procurement of the specified numbers of each UUV variant.

General point cost estimates of programs based on a variable number of UUVs can be extrapolated from Figure 62.

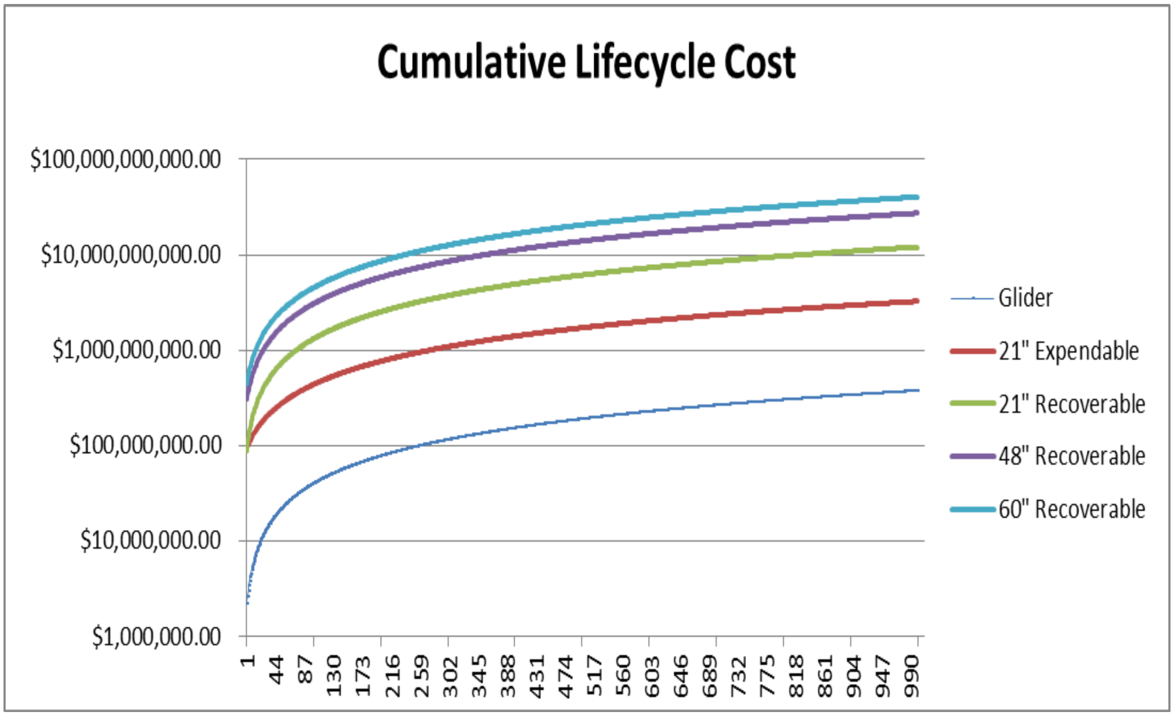

Figure 62. Cumulative Life-Cycle Costs vs. UUV Quantity in FY13 Dollars. The costs of up to 1000 UUVs of each variant can be extrapolated from the respective trend lines. Note that the cost is graphed on a semi-log scale.

Chapter Summary

Cost vs. Weight provides the best cost estimating relationship for UUVs. In general, the more the UUV weighs, the greater the cost. The weight normally corresponds to the UUVs physical dimensions. This concept is consistent with expectations, since large UUVs are able to house and power more capable payloads and sensors.

Energy costs in the form of batteries are the most significant cost driver for O&S cost. Cost estimation showed that if UUVs do not require recoverability then they should be designed specifically for expendability and use less expensive power alternatives.

The next chapter consolidates all of the analysis up to this point and provides a recommended force structure for achieving the mission objectives derived in the 2024 UUV CONOPS.

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IX. FINAL DELIVERABLE: RECOMMENDED FORCE STRUCTURE

Serving as the final deliverable to this study, the recommended force structure is derived from over a years' worth of UUV research and analysis conducted by the Naval Postgraduate School, Systems Engineering Analysis (SEA) project team.

The final force structure is foundationally based upon the assets required to execute the 2024 UUV CONOPS, as described in detail in Chapter V. This CONOPS is designed around a forward deployed naval fleet, tasked with battlespace preparation in a heavily contested A2AD environment. In order to increase survivability and reduce risk to manned platforms, UUVs are deployed to carry out far-forward operations, such as ISR, MILDEC, MCM, and offensive attack operations.

A. RECOMMENDED UUV CHARACTERISTICS:

1. UUV Physical Size Dimensions

Two approximate UUV sizes are recommended to most effectively execute the proposed CONOPS:

1. 48" – 60" diameter LDUUVs capable of being launched from ULRM equipped submarines or from an LCS. The maximum size of 60" is constrained by the size of the Virginia Payload Module and SSGN missile tube diameters.
2. 21" diameter or smaller UUVs capable of being launched from all manned platforms. The maximum size of 21" is constrained by current torpedo tube diameters.

Generally speaking, baseline designs should approach the maximum diameters above, to allow for the greatest amount of mission flexibility. Larger vehicles allow for larger and more capable sensors, and increased energy capacity. The maximum length of both variants is approximately 20ft based on the constraints of the submarine launch mechanisms.

2. UUV Mission Design Considerations

a. LDUVV Mission Design

Based on analysis, LDUUVs are required for missions involving persistent ISR and offensive attack. These vehicles must have the most advanced and capable sensors of all UUV variants, to be able to collect, transmit, and receive critical mission data. The increased propulsion capability inherent to a LDUUV is also required to carry heavy weaponry for engaging multiple enemy surface and subsurface combatants.

Modeling and simulation of the attack missions shows that LDUUVs are not an overly effective platform for traditional, open ocean ASW/ASUW missions. Instead, LDUUVs need to be designed consistent with the SEA-17B Advanced Undersea Weapon System (AUWS) proposal that is now being funded by the Office of Naval Research. This allows for LDUUVs to be deployed to the opening of an enemy harbor or chokepoint, conduct persistent ISR operations in this location, and when required, fire offensive weaponry at targets of interest.

When compared to the 21" UUV variants, LDUUVs need to have a much higher probability of successful return to a recovery platform (Recoverability). As such, design factors related to obstacle avoidance and automated target recognition (ATR) are critical enablers for the LDUUV program. The high cost of LDUUVs will lead to relatively low procurement quantities, and to achieve significant return on investment it is beneficial to be able to use the LDUUV for multiple missions. Recoverability of a LDUUV is the ideal, but in no means a strict requirement. If an LDUUV is able to either destroy or provide a mission kill to even one enemy SSN or surface combatant attempting to leave port, the cost vs. benefit of the LDUUV is more than sufficiently justified.

b. 21" UUV Mission Design

Modeling and simulation of all mission areas show benefits of using 21" UUV variants. 21" UUVs provide significant capabilities but at much lower costs than LDUUVs. However, the small size restricts sensor capability, payload size, and overall endurance.

Much of the analysis effort focuses on exploring the application of low cost, expendable 21” UUV variants. Both the IO and attack mission areas show that there is no requirement, nor is it desired, to have the 21” UUV return to a recovery platform. This facilitates significant cost savings of UUV design, especially in regards to power source alternatives. The ISR and MCM mission areas also revealed that expendability is an important factor, not so much in that these UUV variants should be designed for expendability, but that mission planners should expect that many of the UUVs sent out on missions may not return to recovery platforms.

The MCM Q-route mission area analysis reveals that multiple 21” UUVs are the most effective platforms to carry out mine localization and neutralization due to the greater area of coverage afforded by multiple smaller UUVs, compared to that of one LDUUV. Critical design factors require the UUVs to accurately localize and transmit mine locations to a receiving platform. Highly capable automated target recognition (ATR) systems are a critical enabler for 21” MCM UUVs, to be able to distinguish mines from cluttered environments and reduce post mission analysis (PMA) time. The smaller size also allows for greater flexibility in regards to the platforms involved with launch and recovery operations.

The IO decoy and deception mission area analysis reveals that 21” UUVs are an ideal platform, due to the fact that these systems are designed purely as expendable platforms. If a submarine captain is attempting to lure an enemy away from his operating position through the use of an advance UUV decoy, the captain surely would not then attempt to place his submarine at risk by trying to recover the decoy. The IO UUV payload is the critical enabler, in order to allow the UUV to effectively simulate the signature of a friendly submarine. The 21” size also allows for quick reaction times in regard to UUV deployment, thereby reducing the time that the submarine is held at risk during UUV launch.

The ISR mission area analysis reveals that 21” UUVs should be deployed when there is a substantially high risk of the UUVs being unable to successfully return to a recovery area or when you need quick reaction, short duration ISR missions. Example missions include shallow water ISR missions within enemy ports and harbors. Design

factors related to secure, time critical data transmissions are critical enablers for the 21” ISR variant. The smaller size also allows for greater launch and recovery platform flexibility.

The offensive attack mission area analysis reveals that 21” UUVs are essentially advanced torpedoes. The concept of a 21” attack UUV closely resembles the ongoing developmental programs like the modular undersea heavyweight vehicle (MUHV) and the improved submarine launched mobile mine (ISLMM). These programs essentially overhaul and upgrade aging MK-48 torpedoes to provide options for short range ASW/ASUW attack missions. ATR is the critical enabler for the 21” attack UUV, to provide acceptable levels of target discrimination.

B. SUSTAINED UUV FORCE STRUCTURE QUANTITIES

The required number of vehicles is derived from each individual mission area. Assumptions are made in regards to the type of operation to be undertaken and the requisite number of assets required to achieve the operational objectives. These assumptions are based upon a combination of quantitative and qualitative factors investigated during the modeling, simulation, analysis of alternatives, and cost estimation analyses performed over the duration of this study.

In the MCM mission area the force structure is based upon an assumed need for a submarine or high value unit (HVU) to enter and exit a potentially mined area 10 times. Four 21” recoverable UUVs are used for every transit through a minefield. In the IO mission area, the force structure is based upon the assumption that 50% of a 60 submarine fleet is deployed at any given time, and each deployed submarine is outfitted with two 21” expendable IO decoy UUVs. The force structure for ISR and attack operations is based on dual UUV coverage of four target areas, such as enemy ports or harbors, for 30 day durations. Recommended UUV quantities are provided in Table 34.

2024 Operational UUV Force Structure		
Mission	**UUV Type**	**Quantity**
ISR and Attack	LDUUV	26
ISR	21" Recoverable	25
Attack	21" Expendable	48
MCM	21" Recoverable	96
IO	21" Expendable	72
Total Sustained UUV Force Structure Based on Recommended Size		
	LDUUV	**26**
	21" Recoverable	**121**
	21" Expendable	**120**

Table 34. Recommended Sustained UUV Force Structure. The UUV quantities for each mission area and the total force size based on UUV size are included. Goal is to reach and maintain these sustained force structure levels.

Initially, a linear optimization model was developed to determine the force structure. The goal of the optimization model is to minimize cost while satisfying the mission requirement constraint and giving consideration for platform embarkation constraints. The model begins with a set of assumptions on the number of delivery platforms available as well as the carrying capacity of those platforms. It is assumed that three attack submarines and four LCS's are available in theater at the onset of hostilities. It is assumed that the LDUUV will be part of the force structure and that each attack submarine will embark at least one LDUUV and each LCS will embark two LDUVs. The total carrying capacity of an attack submarine is one LDUUV and the LCS has the capacity to carry four LDUUVs. Stow space for 21" UUVs also affects the optimization. An attack submarine is assumed to have seven spaces available for stowage of 21" UUVs in the torpedo room and each LCS is assumed to have eight stowage spaces available for 21" UUVs. Another assumption is that the force is in a wartime scenario where ISR missions will be conducted with UUVs and SSNs will be part of the force structure that executes attack missions. LDUUVs are also assumed to be multi-mission vehicles that can execute both attack and ISR missions.

The input data for the model is based upon our cost data and modeling output. The attack modeling output that is utilized is the mean number of enemy kills per vehicle. The ISR model output is from the endurance model with total endurance hours per vehicle being the key measure of performance. It should be noted that all assumptions discussed are modifiable and in essence provide a framework for recommending an overall force structure. Shown below is the development of the linear optimization model.

<u>Objective function</u>

$$\text{Min}\, Z = \sum_{m=1}^{5}\sum_{n=1}^{5} C_m x_n$$

<u>Variables</u>

X_1 = 21” expendable UUV

X_2 = 21” recoverable UUV

X_3 = 48” LDUUV

X_4 = 60” LDUUV

X_5 = SSN

<u>Constants</u>

C_1 = 21” expendable UUV cost

C_2 = 21” recoverable UUV cost

C_3 = 48” UUV cost

C_4 = 60” UUV cost

C_5 = SSN cost

E_1 = 21” expendable UUV attack effectiveness

E_2 = 21” recoverable UUV attack effectiveness

E_3 = 48” UUV attack effectiveness

E_4 = 60” expendable UUV attack effectiveness

E_5 = SSN attack effectiveness

I_1 = 21” expendable UUV ISR effectiveness

I_2 = 21” recoverable UUV ISR effectiveness

I_3 = 48” UUV ISR effectiveness

I_4 = 60” expendable UUV ISR effectiveness

I_5 = SSN ISR effectiveness

<u>Constraints</u>

Effectiveness for offensive attack

$$\sum_{m=1}^{5}\sum_{n=1}^{5} E_m x_n \geq 13$$

where 13 is the minimum number of required enemy kills (determined from modeling output)

Effectiveness for ISR

$$\sum_{m=1}^{5}\sum_{n=1}^{5} I_m x_n \geq 5760$$

where 5760 is the is the minimum number of required coverage hours (determined from modeling output)

LDUUV constraint

$$11 \leq \sum_{n=3}^{4} x_n \leq 19$$

Stow space availability

$$\left(\sum_{n=1}^{2} x_n\right) + 7\sum_{n=3}^{4} x_n \leq 154$$

where 154 is the total number of stow spaces available

SSN requirement

$$x_5 \geq 3$$

Integer constraint

$x_n = \text{int}, \forall n = 1, \ldots, 5$

Non-negativity constraint

$x_n \geq 0, \forall n = 1, \ldots, 5$

Figure 63 summarizes the output of the optimization model for the quantity of vehicle.

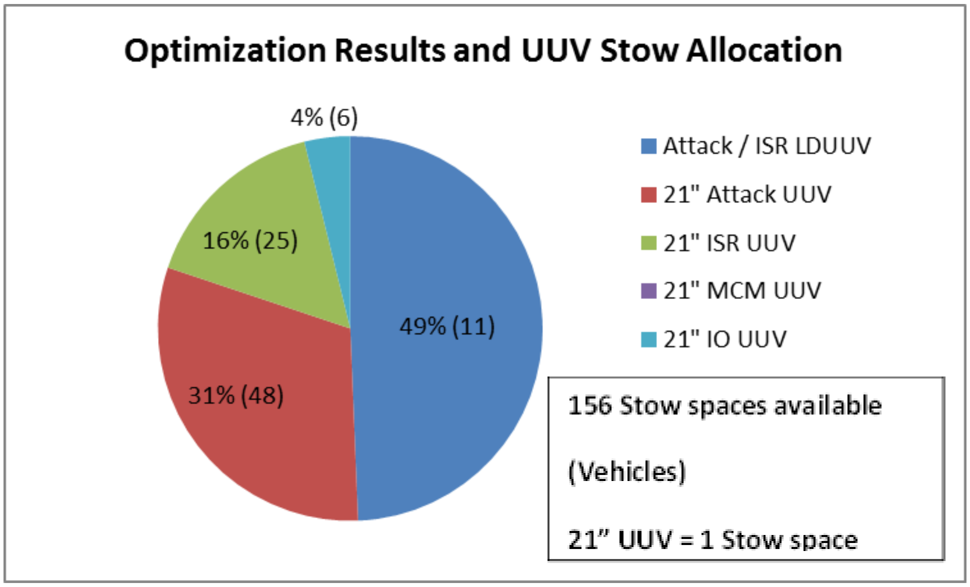
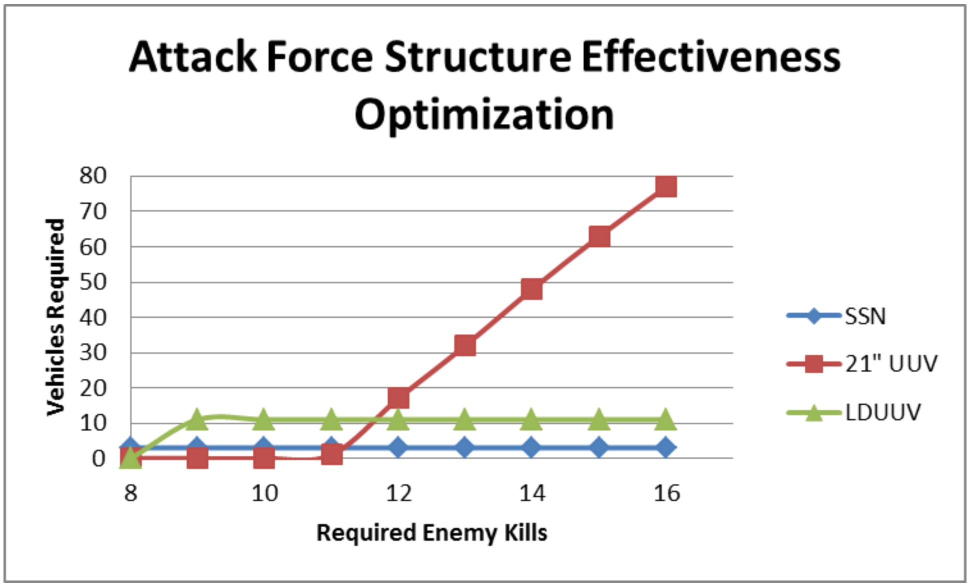


Figure 63. Linear Optimization Model Output Summary. The pie chart shows the optimal quantity of each type of UUV based on the linear optimization model and the proportion of stow space each quantity of UUVs is allocated to.

The outputs of the optimization model are not surprising. Cost analysis in Chapter VIII showed that expendable UUVs are significantly cheaper than recoverable UUVs, hence the reason the expendable alternatives are the optimal choice when the objective is to minimize cost. The project team agreed however that a force with no recoverable UUVs would not be best recommendation. The results of the optimization model provide bounds on which to generate a mixed force structure of 21-inch UUVs and LDUUVs. By varying the number of enemy kills required and ISR coverage hours required it can be shown how 21-inch vehicles are added to the force structure as requirements change. Figure 64 shows a graphical representation of how the force structure changes as a result of requirement changes.



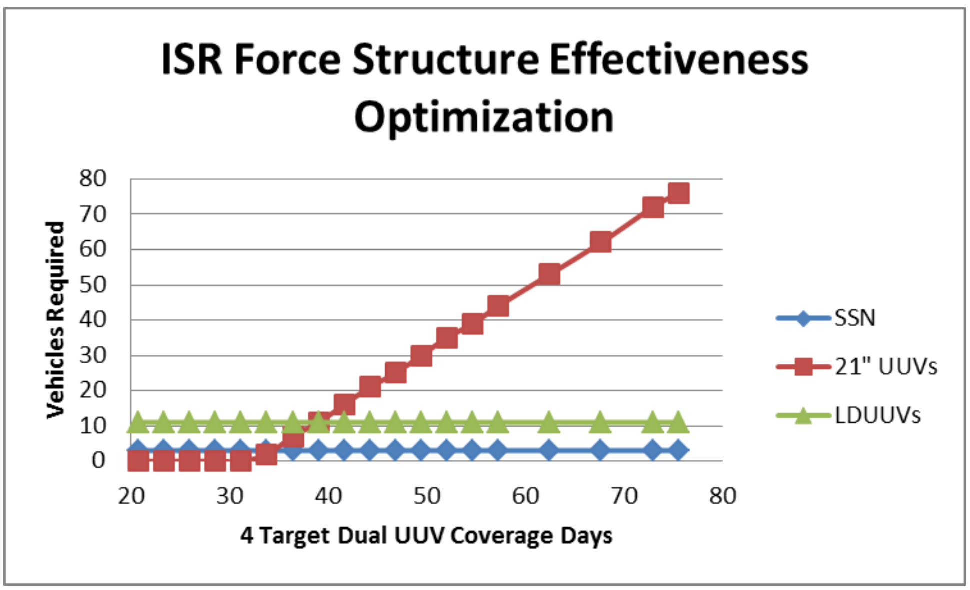


Figure 64. Force Structure Changes from Requirements Changes. The charts show how the force structure changes as a result of varying the number of enemy kills required and ISR coverage hours required.

After achieving the base requirement, the ISR and attack optimization models were reconciled to achieve the maximum effectiveness achievable for both mission areas within the available stow space. The final result was 11 dual mission LDUUVs, 25 21-inch ISR UUVs, and six 21-inch IO UUVs. This results in a total of approximately 14 enemy kills and 46 dual UUV ISR coverage days.

Other assumptions used to determine the total force structure include a standard 20% of vehicles unavailable for operational use due to various maintenance activities. This percentage is consistent with trends observed in UAV squadrons.

Based on modeling and simulation of a highly congested maritime environment, operational UUV loss rates are conservatively estimated at approximately 20 percent based upon modeling efforts. This factor led many of the modeling and analysis results to suggest that for a single mission, expendable UUVs are the favored variant. However, this did not account for the additional utility obtained by a recoverable variant. Figure 65 shows that in the worst case scenario based upon the Geometric distribution expected value function. In the most optimistic scenario of a 2.5 percent loss rate, the number of expected missions for a recoverable UUV is 40 missions. In the most pessimistic scenario of a 20 percent loss rate, 5 missions could be expected of a vehicle. If the true loss rate is somewhere in between, for example 8.75 percent, 11 missions could be expected of a UUV.

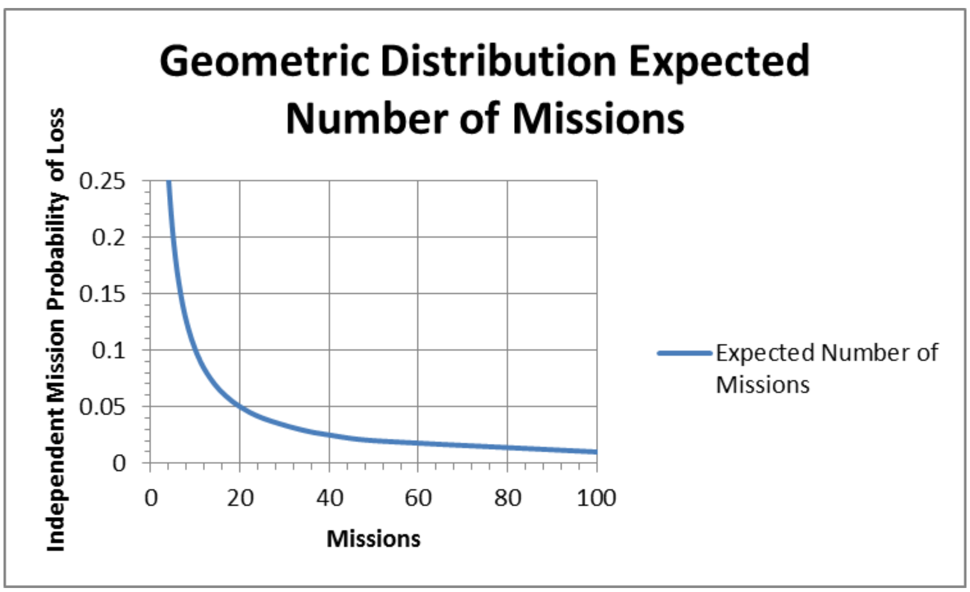


Figure 65. Expected number of UUV missions based on Geometric Distribution. In the most optimistic scenario of a 2.5% loss rate, the number of expected missions for a recoverable UUV is 40 missions. In the most pessimistic scenario of a 20% loss rate, 5 missions can be expected.

This qualitative and quantitative analysis drives the conclusion that 21” recoverable UUVs provide greater utility to the ISR and MCM mission sets. The total number of missions completed ratio of recoverable UUVs vs. expendable UUVs also overcome the cost saving advantages seen with expendable UUVs.

C. PROPOSED FORCE STRUCTURE LIFE-CYCLE COST

Table 35 illustrates the life-cycle cost (LCC) for three separate UUV force structure options. UUV program costs include RDT&E, O&S, procurement, & disposal costs. The cost of one Virginia Class Submarine is included for general order of magnitude cost comparisons. The Virginia sub cost includes procurement and all O&S cost for a 20-year period, but does not incorporate the cost for RDT&E and disposal.

Vehicle	Exp, Rec, & LDUUV	Rec & LDUUV	Exp & LDUUV	SSN-774
21" Expendable	$ 1,126,993		$ 1,560,168	$ -
21" Recoverable	$ 1,318,475	$ 2,499,210	$ -	$ -
60" Recoverable	$ 1,207,474	$ 1,207,474	$ 1,207,474	$ -
SSN-774	$ -	$ -	$ -	$ 4,076,285
Total (FY13$K)	$ 3,652,942	$ 3,706,684	$ 2,767,642	$ 4,076,285

Table 35. UUV Force Structure LCC Alternatives in FY13K Dollars. Cost comparisons for three alternative programs are shown. The recommended mixed force structure and LCC are shown in the second column under Exp, Rec, & LDUUV.

The total life-cycle comparisons use the cost estimation methods explained in Chapter VIII. Total numbers of vehicles acquired over the life cycle for each alternative are shown in Table 36. These are the numbers of UUVs required to maintain and sustain the force structure shown in Table 34. In regards to loss rates, a 2.5% operational UUV loss rate is assumed. In addition, a constant 20 vehicle expenditure per year for the 21” expendable units are factored in for peacetime operations and training.

Force Structure	21" Recoverable	21" Expendable	LDUUV
Exp, Rec, & LDUUV	167	440	35
Rec & LDUUV	334	0	35
Exp & LDUUV	0	560	35

Table 36. Total UUV Procurement for 20 Year Life Cycle. In order to sustain the UUV fleet structure allowances for anticipated mission losses, training units, and maintenance down time are factored into the total recommended procurement quantities. The recommended force structure procurement is shown in the Exp, Rec, & LDUUV row.

Figure 66 provides a graphical representation of Tables 35 and 36.

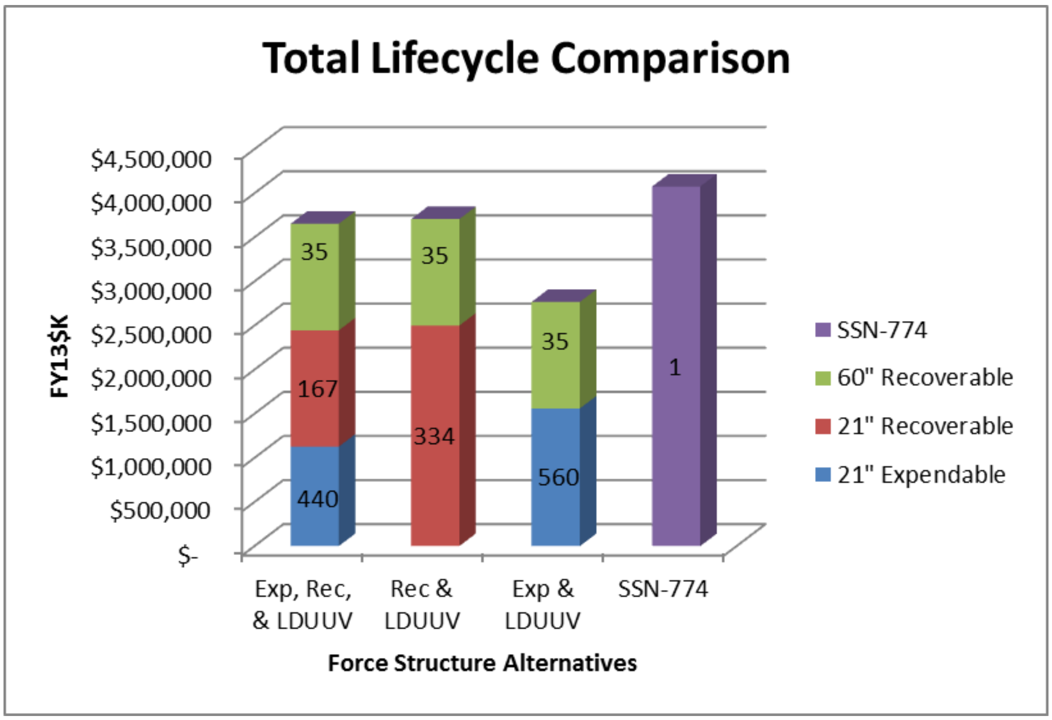


Figure 66. 20 Year Total UUV Procurement and LCC in FY13K Dollars. Three alternatives are analyzed for total life-cycle costs and procurement levels required to maintain and sustain the UUV fleet force structure.

An initial takeaway from this graph may be that the 21" expendable only and LDUUV alternative is preferred due to having the lowest LCC. This is not the case primarily due to the number of missions feasible per alternative as shown in Figure 67. The 21" expendable options are considered to be "one and done." Assuming a very conservative

average of eight missions executed per 21” recoverable UUV (derived from Figure 65), over twice the number of missions can be executed by the mixed expendable, recoverable, and LDUUV alternative. The 21” recoverable only and LDUUV option adds additional cost, with no value added, due to the fact that the 21” variants for IO and attack do not need to be recoverable.

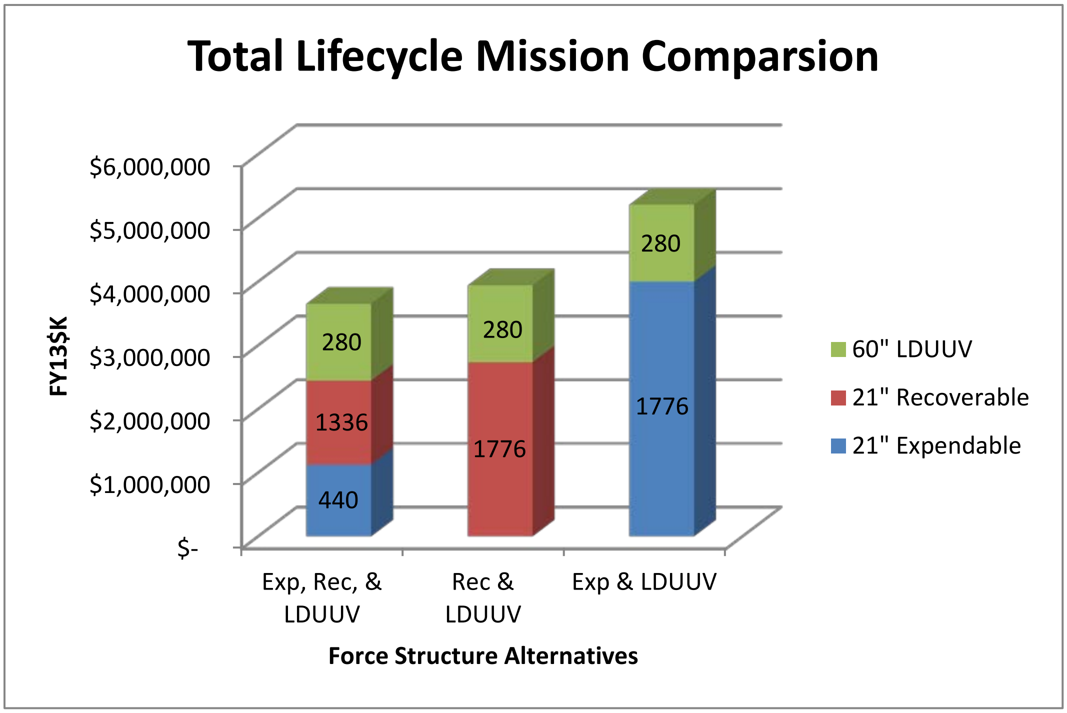


Figure 67. Total Life-Cycle Cost Comparison Based on Equal Numbers of Missions Completed. To realize the true cost savings associated with the recommended force structure, it is necessary to make cost comparisons on a per mission basis.

D. TIME PHASED UUV IMPLEMENTATION STRATEGY

The primary purpose of a time phased implementation strategy is to provide capabilities to the operational fleet as assets become available. The proposed timeline in Table 37 assumes that all three UUV variants will have reached full operational capability by 2018 and have entered full scale production. Production levels are initially high in order to increase force levels. As total UUV fleet size reaches sufficient operational levels, production requirements drop in order to maintain the desired baseline force structure as shown in Figure 68.

120 - 21" Exp / 120 - 21" Rec / 26 - LDUUV Lifecycle Acquistion Plan			
Fiscal Year	**21" Expendable**	**21" Recoverable**	**LDUUV**
FY14	0	0	0
FY15	0	0	0
FY16	0	10	0
FY17	20	10	0
FY18	30	15	0
FY19	30	15	2
FY20	30	15	3
FY21	30	15	3
FY22	30	15	3
FY23	30	15	3
FY24	30	15	3
FY25	30	15	3
FY26	20	3	3
FY27	20	3	3
FY28	20	3	3
FY29	20	3	1
FY30	20	3	1
FY31	20	3	1
FY32	20	3	1
FY33	20	3	1
FY34	20	3	1
Total FY13SK	**$ 1,126,993**	**$ 1,318,475**	**$ 1,207,474**

Table 37. UUV Force Structure Acquisition Timeline. As all variants enter full rate production, yearly acquisition levels are initially high to raise UUV levels to acceptable operational levels. Production levels then decrease to maintain desired UUV fleet levels.

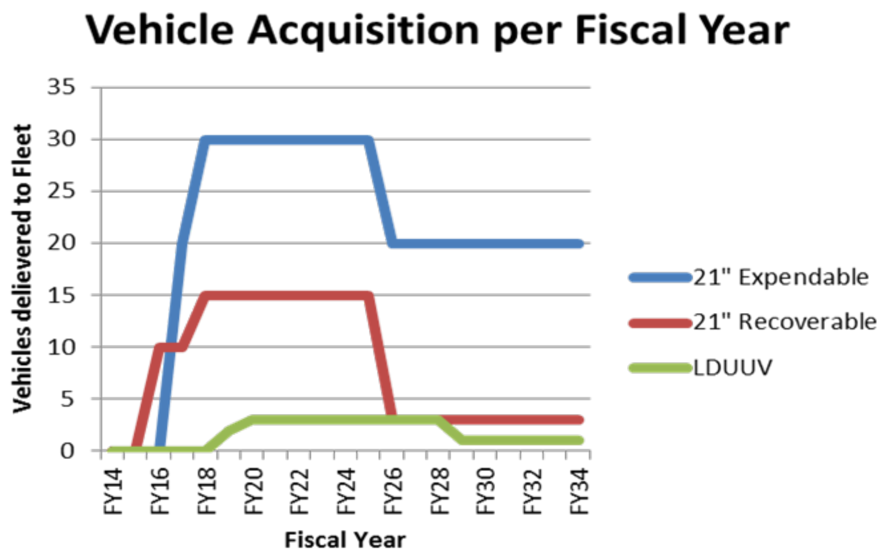


Figure 68. Total UUV Acquisition Levels per Year. This figure provides a visualization of Table 37. As all variants enter full rate production, yearly acquisition levels are initially high to raise UUV levels to acceptable operational levels. Production levels then decrease to maintain desired UUV fleet levels.

This implementation provides the assets necessary to effectively execute the proposed A2AD UUV CONOPS by 2024. Figure 69 illustrates how the implementation plan in Table 37 effectively achieves and sustains UUV force levels required for operations.

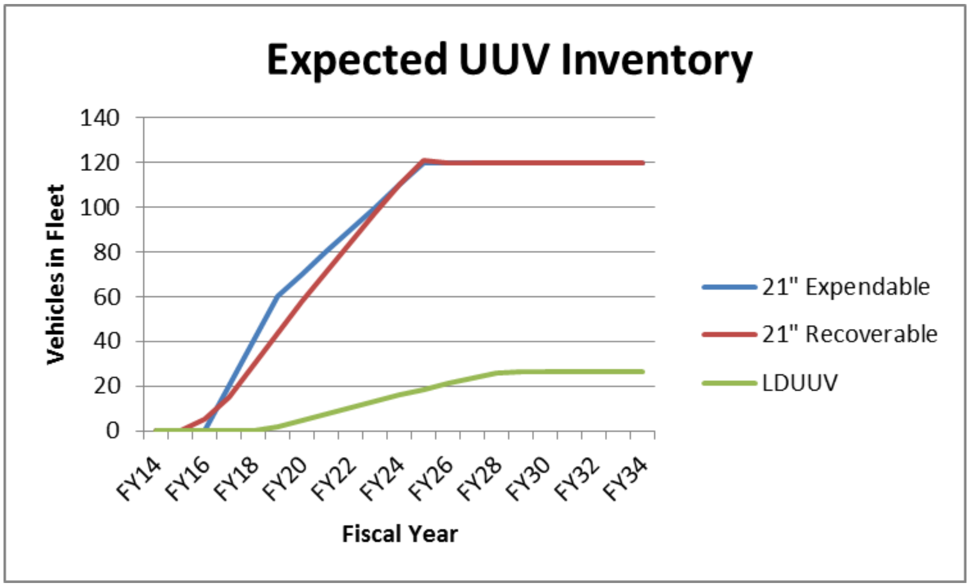


Figure 69. UUV Force Structure Inventory by Year. As all variants enter full rate production, yearly acquisition levels are initially high to raise UUV levels to acceptable operational levels. Production levels then decrease to maintain desired UUV fleet levels.

E. DOTMLPF CONSIDERATIONS

1. Facilities

The cost analysis used to generate the LCC of the recommended acquisition program includes projected costs for all physical materials, to include the cost of production and support facilities. An exception to this is the 21” expendable UUV variant outfitted with an explosive charge for offensive operations, which may be required to be maintained at current ammunition handling and storage facilities. The UUV squadrons will require adequate facilities to store and maintain all UUVs not currently embarked onboard deployed units. The location of the UUV squadron or squadrons would benefit by being located adjacent to Air Mobility Command transportation assets. This allows for large numbers of UUV assets to be deployed anywhere in the world in a relatively short amount of time.

2. Organization, Personnel, and Training

The organization of the UUV fleet is highly dependent on platform size and capabilities. Based on the highly technical LDUUVs and 21” recoverable UUVs recommended as part of our force structure, specialized enlisted personnel or civilian

contractors will be required to operate and maintain the UUVs and associated launch and recovery equipment.

UUV assets are intended to be rotational units that are moved from platform to platform to minimize the total number of UUVs required. This rotational concept also benefits greatly by having squadron based crews, much like the organizational concepts employed by existing helicopter squadrons. It would be fiscally imprudent to have the necessary number of personnel with the required Naval Enlisted Codes (NEC) onboard all supporting platforms, especially when UUV assets are not embarked.

Notional operations consist of UUV squadron personnel being embarked onboard the host platform in the form of a detachment. LDUUVs are assumed to be deployed in detachments of one to two vehicles, with three individuals for operations and maintenance per detachment. 21" recoverable UUVs are assumed to be deployed in detachments of six vehicles, with two individuals for operations and maintenance. Notional deployed manning requirements are as follows:

LDUUV manning will be approximately 39 personnel in 13 detachments.

21" recoverable manning will be approximately 40 personnel in 20 detachments.

A total of 79 personnel are recommended for detachment operations and maintenance. Considering the fact that not all personnel can be constantly deployed, the total personal required for the squadron is essentially doubled. The final number of operations and maintenance personnel is approximately 160. These personnel will be assigned a specialized NEC, and this will be considered a primary sea duty billet. Additional personnel allowances for leadership, logistics and administrative functions increase the total squadron manning to approximately 175 personnel.

21" expendable UUVs are designed with very few shipboard maintenance requirements. The offensive attack variants require essentially the same care that existing torpedoes require. The IO variant is also treated like a torpedo for all intents and purposes. At most the operators will be required to upload mission software requirements. In regards to manning, the recommendation is to have operation and maintenance be conducted by current ships force, as a collateral duty for two currently existing ship crew members. Prospective source rates are Sonar Technician (STG/STS),

Machinist Mates (Submarine Weapons), Gunners Mate (GM), or Electronics Technicians (ET). Selected personnel will receive training on operations and maintenance of expendable UUVs and if required will receive the required NECs.

For all UUV training, it is recommended that the appropriate "C" school be placed in the Catalog of Navy Training Courses (CANTRAC) and developed per the Task Based Curriculum Development Manual (Chief of Naval Education and Training, 2009). Until the appropriate schools can be instituted, ships force should receive on-the-job (OJT) training and augmentation from technical representatives, so that the culture of UUV operations can begin to foster in the United States Naval fleet.

F. CONCLUDING THOUGHTS

For less than the cost of one nuclear powered attack submarine the United States Navy can fund the entire proposed UUV force structure. Not only do the UUVs provide significant offensive capability, they also greatly improve the survivability of submarines and other high value units (HVUs) operating in contested A2AD environments.

UUVs can act as force multipliers and provide critical extensions of capability to existing manned platforms. Based on modeling, simulation, and subsequent analysis, the proposed force structure can supplement two submarines in the ISR and attack roles for a period of approximately thirty days. Based on physical dimensions and inherent risk to manned platforms, UUVs also have the capability to access areas that manned platforms simply cannot, or would not want to access. The use of IO UUVs can decrease submarine loss rates from 8% to 5%. MCM UUVs have the ability to reduce submarine and other HVU loss rates by up to 73% by conducting covert Q-route mapping.

Placing greater quantities of highly capable mission platforms in an environment forces the enemy to expend resources to counter the threats. Otherwise all of the enemies' efforts can be directed towards friendly HVUs. Furthermore the loss or capture of several UUVs by enemy forces does not substantially affect the performance of the overall UUV force structure. Even though many UUVs are designed for recoverability, they are also inherently expendable based on their relatively low costs.

X. RECOMMENDED FUTURE ANALYSIS

Several innovative concepts studied throughout this report show significant promise in regards to undersea dominance. However, with our tasking primarily focused on recommending a UUV force structure capable of performing multiple missions in an A2AD environment, it made it difficult to dedicate significant amounts of time and resources to any one individual concept. Stakeholders that read this report may draw their own conclusions for areas that can benefit from further research, but the following concepts have been self-identified to benefit from future analysis.

Communication and Coordinated Sensing

Modeling and analysis exposed communication as a cornerstone on which UUV mission success will be based upon. Communication is a critical link for relaying data from a UUV to a host platform for command and control functions. Future work that is able to research and determine the dependency of target resolution on data rate and SNR is recommended.

Sensor data sharing between UUVs can potentially dramatically improve battle space effectiveness. Future work for coordinated sensing to include analysis of optimal UUV squad size and configuration for searching, tracking, and deceptive operations against enemy forces is recommended. For more information refer to Appendix E.

Deception and Decoy Operations

Military deception is one of the most cost effective strategies used in preventing successful enemy engagements. Further analysis is recommended that looks at payoff versus risk tolerance for using UUV's to conduct deception operations. In support of this, it is recommended that exhaustive modeling be conducted on distraction based deception that incorporates multiple track plans and the use of multiple decoy UUVs. This research may also need to take place at a higher classification level to explore technologies available or in development.

Analysis of UUV Autonomy and Reliability

UUVs must be highly autonomous and reliable to ensure mission success. Many R&D institutions and naval enterprise corporations are currently studying these critical operating issues. For this reason our report intentionally did not focus on these research areas. But considering the great importance of these capabilities, it is recommended that in depth analysis of the current and projected autonomy levels of UUVs be periodically revisited by independent research groups.

Analysis of 12” (MK 54 sized) UUVs

The USN has several torpedo launch systems that utilize 12.75” diameter tubes. An analysis of the power, technology, and payload capabilities of a 12.75” diameter UUV is recommended. This could bring significant UUV capabilities to surface combatants and utilize existing launch equipment.

Analysis of Glider Mine UUVs

The concept of mobile mine fields, using explosive UUV gliders, showed significant combat capability at a relatively low cost in the modeling and simulation portion of this study. The decision was made to not include them in the force structure due to the need for further analysis concerning command and control and the ethical concerns for such a weapon.

Analysis of Manpower Requirements

Although a notional organizational structure and manpower requirement level is presented, more extensive analysis is recommended to determine the most effective and cost efficient manpower solution for UUV operation and maintenance. Analysis of the maintenance levels required by ships force and/or civilian contractors needs to be completed. With the exception of full overhauls, if all maintenance and operations are to be conducted by ships force, this will also greatly affect the specialized training requirements.

Analysis of Launch and Recovery Options

The method of deployment and recovery is an important part of using UUVs. LCS and ULRM equipped submarines are the only considered launch platforms for this study. Therefore, an in depth analysis should be conducted to determine effectiveness of various launch and recovery options for a greater variety of platforms.

Analysis of Mission Payloads

This report focused on a broad approach of analyzing various vehicles with standard payloads. Future work is needed to determine modular payloads and the payload effects on power consumption and the total endurance of the UUVs.

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APPENDIX A: STAKEHOLDER INTERACTIONS

Stakeholder	Organization / Role
Mr. Mike Novak	OPNAV N9IB
Mr. Charles Werchado	Executive Director of the Submarine Force
RDML Barry L. Bruner	Director, Undersea Warfare Division N97
RADM (Ret.) Winfred (Jerry) Ellis	NPS SME Advisor
RDML (Ret.) Richard D. (Rick) Williams III	NPS SME Advisor
Bill Glenney	Deputy Director CNO Strategic Studies Group
CAPT Doug Marble	Assistant Chief of Naval Research
CAPT Jeff Jablon	SUBDEVRON 5
Douglas Humphreys	Vehicle Control Technologies (VTC)
Pierre Corriveau	NAVSEA
Scott Truver	Gryphon Technologies
Ronald Merlene	PEO LCS
Steve Castelin	ONR X20
David L Kubik	John Hopkins APL
Jon Wood	Seebyte
Jeff Currer	Johns Hopkins (Former Submarine Commanding Officer)
David E Everhart	NSWC MIW Advanced Concept
LCDR Matt Voracheck	SUBDEVRON 5
Ross Lindman, Dave DeMarino	Columbia Group LDUUV
Phillip McGillivary	Science Liaison for U.S. Coast Guard
Jeff Smith	COO Bluefin Robotics
Francois Leroy	Senior VP Liquid Robotics
Tom Noonan	Director Business Development – Sea Power Systems, Kongsberg Defense Systems
Dan Kucik	ONR X22 Automation and Dynamics
Jim Bellingham	COO MBARI
Dave Scheid	NAVSEA Future Fleet Concepts

Stakeholder	Organization / Role
Daniel Lawrence	General Dynamics, Senior Manager Advanced Programs

APPENDIX B: TRANSPORTATION ANALYSIS

To determine a maximum size a basic transportation analysis is conducted that examined vehicle size in the context of transportation system limitations and a simulation that examined the time required for a UUV to deploy to a target area. This transportation analysis utilized the dimensions and weights associated with the Deep Submergence Rescue Vehicle (DSRV) and the Advanced Seal Delivery System (ASDS).

Both vehicles exhibited many characteristics and functions of a UUV, were designed to be air mobile, and analogous comparisons can be made. The ASDS weighs approximately 55 tons, is cylindrical in shape, and has dimensions of 65 feet in length and an 8 foot diameter. The DSRV weighs 38 tons, is cylindrical in shape, and has dimensions of 49 feet in length and an 8 foot diameter. If the volume is approximated based upon the dimensions of a cylinder a weight per volume can be calculated. The weight per volume of the ASDS and the DSRV is calculated and the average weight per volume is 504kg/cubic meter. This weight per volume is then utilized to make estimations of proposed vehicle weight based upon vehicle length and diameter. The ratio of length to diameter is averaged for both vehicles and then held constant for consistency. The estimations of vehicle length to weight are then plotted and compared to transportation system constraints as shown in Figure B-1.

The basic transportation analysis considers movement to the theater of operations via strategic airlift, ocean cargo transport, and pre-positioning and stationing in the forward area. The strategic airlift capabilities include U.S. Air Force C-5, C-17, and C-130 transport aircraft. The weight limits associated with these aircraft are 270,000lbs, 170,900lbs and 34,000lbs respectively. Other limitations that apply to the transportation analysis are weight limits associated with the interstate highway system. Vehicles on the Interstate Highway System are limited to 80,000 pounds. Beyond 80,000 pounds a combination of rail and sea transport would be required to transport the vehicle to the theater of operations. The examples of the ASDS and DSRV show that even though a single vehicle can be designed to be air mobile, deployment of more than one vehicle at a time could be very problematic depending on UUV size. The insight gained from this

analysis has a direct impact on the transportability of the weapon system and the ability to employ effective combat power in a timely manner.

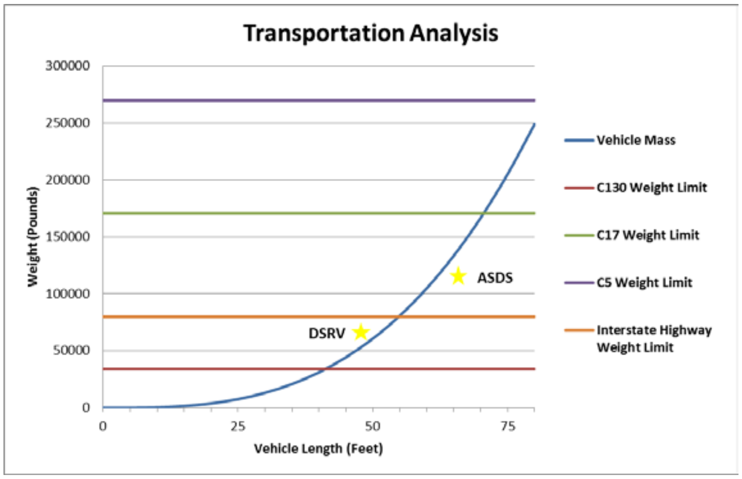

Figure B-1: Weight vs. UUV Transportation Analysis

The optimum goal is to deliver credible combat power to the area of operations as quickly as possible. In the transportation analysis a basic simulation is conducted to evaluate the need for system transportability and mobility. Two scenarios are compared via simulation to assess how quickly a UUV can transit to the target area. The first case is a pre-positioned, in-theater pier launched UUV that transits to the target area under UUV power alone. The second scenario is a U.S. based UUV element that deploys upon order to the theater and then is transported from in theater base via LCS or SSN to the target area. This scenario takes in to account the time to embark and debark the aircraft, aircraft transit time, embarkation on to the transport ship, and then the time required for the transport ship to transport the UUV to the target area. In the simulation values are chosen for embarkation and debarkation times, transit distances and transit speeds are varied using a rand between function in Excel. It is assumed with this distribution that the values are normally distributed. Table B-1 represents the values utilized in the simulation.

Transportation Analysis Input Data Table				
	U.S. Based / Air Mobile		**Forward Based / Pier Launched**	
	MIN	MAX	MIN	MAX
Aircraft Embarkation (HR)	8	12	0	0
Aircraft Transit (HR)	20	36	0	0
Aircraft Debarkation (HR)	8	12	0	0
Ship Embarkation (HR)	8	12	0	0
Target Area Distance (NM)	250	1400	250	1400
Speed Enroute (KT)	18	22	5	10

Table B-1: Transportation Analysis Data

The result of the simple simulation shows that the air mobile mean time to target area is 99.4 hours with a standard deviation of 17.8 hours. The Pier launched mean time to target area is 115.7 hours with a standard deviation of 55.5 hours. To verify the difference in the means is statistically significant, a hypothesis test for means is conducted at the .05 significance level. The null hypothesis was that the difference in the means was zero. The p-value is less than the significance level therefore we rejected the null hypothesis; showing there is a difference in the means. An ANOVA also shows that the difference in the means is statistically significant. Consolidated results are show in Table B-2.

Transportation Analysis z-Test: Two Sample for Means		
	Air Mobile	*Pier Launched*
Mean	99.53253955	116.3951683
Known Variance	317.84	3081.68
Observations	10001	10001
Hypothesized Mean Difference	0	
z	-28.92265732	
P(Z<=z) one-tail	0	
z Critical one-tail	1.644853627	
P(Z<=z) two-tail	0	
z Critical two-tail	1.959963985	

Table B-2: UUV Average Transportation Time (Hours)

Also of interest in the results is the descriptive statistics, histograms and box plots associated with each data set as shown in Figure B-2. Air transportable UUVs provide a more predictable arrival time in the target area. Pier launched UUVs take longer to arrive, have greater variability and can have arrival times of up to 280 hours. This maximum is double that of the air transportable UUV maximum time. Assuming worst case conditions

for both UUVs, the pier launched UUV would arrive up to 5 days later than the air mobile variant. The transportation logistics associated with a large vehicle limits the application of the weapon system in time critical hostilities. It is unlikely an adversary will allow the United States Navy the amount of time required for adequate build-up of force size and deployment to the target area.

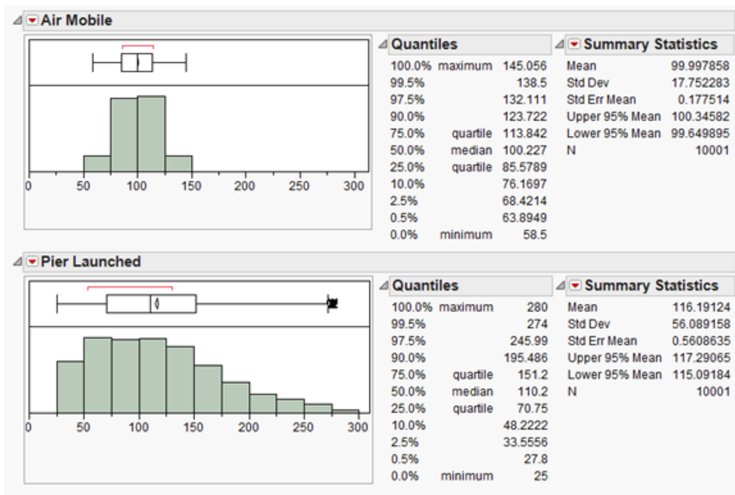

Figure B-2: ANOVA Transportation Data (Hours)

APPENDIX C: MODELING AND SIMULATION DATA

A. UUV ENDURANCE PERFORMANCE DATA TABLES

21" UUV Performance Characteristics			
Speed (Knots)	**Power (kWh)**	**Endurance (Hours)**	**Distance (NM)**
1.00	0.00	45.70	45.70
2.00	0.10	39.16	78.31
3.00	0.30	32.89	98.67
4.00	0.59	26.91	107.62
5.00	1.01	21.33	106.66
6.00	1.59	16.53	99.17
7.00	2.38	12.66	88.62
8.00	3.42	9.68	77.43
9.00	4.75	7.44	66.95
10.00	6.42	5.77	57.71
11.00	8.45	4.53	49.80
12.00	10.90	3.60	43.14
13.00	13.81	2.89	37.57
14.00	17.21	2.35	32.90
15.00	21.15	1.93	28.98
16.00	25.66	1.60	25.67
17.00	30.80	1.35	22.87
18.00	36.60	1.14	20.48
19.00	43.10	0.97	18.43
20.00	50.34	0.83	16.67
21.00	58.37	0.72	15.13
22.00	67.22	0.63	13.80
23.00	76.94	0.55	12.63
24.00	87.56	0.48	11.59
25.00	99.14	0.43	10.68

48” UUV Performance Characteristics			
Speed (Knots)	**Power (kWh)**	**Endurance (Hours)**	**Distance (NM)**
1.00	0.40	324.12	324.12
2.00	0.44	315.29	630.57
3.00	0.99	228.92	686.76
4.00	2.16	144.11	576.42
5.00	4.07	89.65	448.23
6.00	6.85	57.93	347.59
7.00	10.62	39.15	274.07
8.00	15.49	27.59	220.68
9.00	21.59	20.14	181.24
10.00	29.03	15.15	151.46
11.00	37.94	11.68	128.48
12.00	48.44	9.20	110.40

60” UUV Performance Characteristics			
Speed (Knots)	**Power (kWh)**	**Endurance (Hours)**	**Distance (NM)**
1.00	0.04	756.07	756.07
2.00	0.49	507.18	1014.35
3.00	1.50	302.86	908.57
4.00	3.29	176.14	704.54
5.00	6.12	106.23	531.17
6.00	10.21	67.46	404.75
7.00	15.80	45.00	314.97
8.00	23.14	31.32	250.54
9.00	32.46	22.60	203.36
10.00	44.00	16.80	168.02
11.00	57.99	12.82	140.99
12.00	74.68	9.99	119.88

B. SENSOR CAPABILITY DATA TABLES

Enemy Subsurface Acoustic Sensor Capabilities					
Range (KM)	Enemy Sub Passive Sonar Vs. SSN/UUV (Pd)	Enemy Sub Active Sonar Vs. SSN (Pd)	Enemy Sub Active Sonar Vs. UUV (Pd)	Fixed Sonar Array Vs. SSN (Pd)	Fixed Sonar Array Vs. UUV (Pd)
0	1	1	1	1	1
1	1	1	1	1	1
2	0	0.2545	0	0.9408	0.9591
3	0	0.1879	0	0.8735	0.91
4	0	0.1439	0	0.788	0.8514
5	0	0.112	0	0.7194	0.8088
6	0	0.087	0	0.6512	0.7583
7	0	0.0684	0	0.5817	0.7078
8	0	0.054	0	0.5186	0.665
9	0	0.0433	0	0.4626	0.6245
10	0	0.033	0	0.4098	0.5823
11	0	0.0256	0	0.3664	0.5453
12	0	0.0193	0	0.3202	0.5047
13	0	0.0148	0	0.2829	0.4675
14	0	0.0119	0	0.2417	0.4216
15	0	0.0071	0	0.2091	0.3901
16	0	0.0048	0	0.1866	0.3613
17	0	0.0035	0	0.1602	0.3312
18	0	0.0028	0	0.1413	0.3069
19	0	0.0018	0	0.1202	0.2782
20	0	0.0011	0	0.1072	0.2548
30	0	0.0006	0	0.0879	0.2271
40	0	0	0	0.0149	0.0777
50	0	0	0	0	0

Enemy Surface Acoustic Sensor Capabilities			
Range (KM)	Enemy Destroyer Passive Sonar Vs. SSN/UUV (Pd)	Enemy Destroyer Active Sonar Vs. SSN (Pd)	Enemy Destroyer Active Sonar Vs. UUV (Pd)
0	1	1	1
1	1	1	1
2	0	0.1732	0
3	0	0.119	0
4	0	0.0825	0
5	0	0.0595	0
6	0	0.0432	0
7	0	0.0331	0
8	0	0.0218	0
9	0	0.0164	0
10	0	0.0115	0
11	0	0.0087	0
12	0	0.006	0
13	0	0.004	0
14	0	0.0023	0
15	0	0.001	0
16	0	0.0005	0
17	0	0.0003	0
18	0	0.0003	0
19	0	0	0
20	0	0	0
30	0	0	0
40	0	0	0
50	0	0	0

Enemy Aircraft Acoustic Sensor Capabilities				
Range (KM)	Enemy Maritime Patrol Sonobuoy Vs. SSN (Pd)	Enemy Maritime Patrol Sonobuoy Vs. UUV (Pd)	Enemy Helo Patrol Sonobuoy Vs. SSN (Pd)	Enemy Helo Patrol Sonobuoy Vs. UUV (Pd)
0	0.08	0.08	0.04	0.04
1	0.08	0.08	0.04	0.04
2	0.08	0.08	0.04	0.04
3	0.08	0.08	0.04	0.04
4	0.08	0.08	0.04	0.04
5	0.08	0.08	0.04	0.04
6	0.08	0.08	0.04	0.04
7	0.08	0.08	0.04	0.04
8	0.08	0.08	0.04	0.04
9	0.08	0.08	0.04	0.04
10	0.08	0.08	0.04	0.04
11	0.07	0.07	0.03	0.03
12	0.07	0.07	0.03	0.03
13	0.07	0.07	0.03	0.03
14	0.07	0.07	0.03	0.03
15	0.07	0.07	0.03	0.03
16	0.06	0.06	0.02	0.02
17	0.06	0.06	0.02	0.02
18	0.06	0.06	0.02	0.02
19	0.03	0.03	0.01	0.01
20	0.03	0.03	0.01	0.01
30	0.01	0.01	0	0
40	0.01	0.01	0	0
50	0.01	0.01	0	0

Enemy Aircraft Radar Sensor Capabilities				
Range (KM)	Enemy Maritime Patrol ISAR Vs. SSN (Pd)	Enemy Maritime Patrol ISAR Vs. UUV (Pd)	Enemy Helo Patrol Radar Vs. SSN (Pd)	Enemy Helo Patrol Radar Vs. UUV (Pd)
0	0.45	0.45	0.45	0.45
1	0.4455	0.4455	0.441	0.441
2	0.441	0.441	0.432	0.432
3	0.4365	0.4365	0.423	0.423
4	0.432	0.432	0.414	0.414
5	0.4275	0.4275	0.405	0.405
6	0.423	0.423	0.396	0.396
7	0.4185	0.4185	0.387	0.387
8	0.414	0.414	0.378	0.378
9	0.4095	0.4095	0.369	0.369
10	0.405	0.405	0.36	0.36
11	0.396	0.396	0.342	0.342
12	0.387	0.387	0.324	0.324
13	0.378	0.378	0.306	0.306
14	0.369	0.369	0.288	0.288
15	0.36	0.36	0.27	0.27
16	0.351	0.351	0.252	0.252
17	0.342	0.342	0.234	0.234
18	0.333	0.333	0.216	0.216
19	0.324	0.324	0.198	0.198
20	0.315	0.315	0.18	0.18
30	0.225	0.225	0	0
40	0.135	0.135	0	0
50	0	0	0	0

Enemy Surface Radar Sensor Capabilities				
Range (KM)	**Enemy Destroyer Vs. SSN (Pd)**	**Enemy Destroyer Vs. UUV (Pd)**	**Enemy Land Based Radar Vs. SSN (Pd)**	**Enemy Land Based Radar Vs. UUV (Pd)**
0	0.45	0.45	0.1	0.1
1	0.45	0.45	0.1	0.1
2	0.45	0.45	0.1	0.1
3	0.45	0.45	0.1	0.1
4	0.45	0.45	0.1	0.1
5	0.45	0.45	0.1	0.1
6	0.45	0.45	0.1	0.1
7	0.45	0.45	0.1	0.1
8	0.45	0.45	0.1	0.1
9	0.45	0.45	0.1	0.1
10	0.45	0.45	0.1	0.1
11	0.45	0.45	0.1	0.1
12	0.45	0.45	0.1	0.1
13	0.45	0.45	0.1	0.1
14	0.45	0.45	0.1	0.1
15	0.45	0.45	0.1	0.1
16	0.45	0.45	0.1	0.1
17	0.45	0.45	0.1	0.1
18	0.45	0.45	0.1	0.1
19	0.45	0.45	0.1	0.1
20	0.45	0.45	0.1	0.1
25	0.45	0	0.1	0.1
30	0	0	0.1	0.1
35	0	0	0	0

UUV Passive Sonar Capabilities					
Range (KM)	**UUV Passive Sonar Vs. Enemy Destroyer (Pd)**	**UUV Passive Sonar Vs. Enemy Submarine (Pd)**	**UUV Passive Sonar Vs. Enemy Active Sonar (Pd)**	**UUV Passive Sonar Vs. Trawling Boat (Pd)**	**UUV Passive Sonar Vs. Merchant (Pd)**
0	1	1	1	1	1
1	1	1	1	1	1
2	0.5343	0.2167	1	0.2729	1
3	0.4578	0.1628	1	0.1804	0.9977
4	0.3875	0.1177	1	0.1213	0.9848
5	0.3458	0.0907	1	0.0868	0.9755
6	0.3058	0.0761	1	0.0613	0.9649
7	0.2684	0.0623	1	0.0406	0.9507
8	0.2355	0.0476	1	0.0269	0.9326
9	0.2168	0.0429	1	0.0182	0.9261
10	0.1934	0.0332	1	0.0113	0.9099
11	0.169	0.0304	1	0.0061	0.8855
12	0.1532	0.0259	1	0.0019	0.8788
13	0.1346	0.0216	1	0.0004	0.8606
14	0.1157	0.0195	1	0	0.8351
15	0.1063	0.0172	1	0	0.8292
16	0.0901	0.0146	1	0	0.8045
17	0.0817	0.013	1	0	0.7959
18	0.0699	0.0108	1	0	0.7693
19	0.0645	0.0084	1	0	0.759
20	0.0528	0.0072	1	0	0.734
30	0.0461	0.006	0.5	0	0.7243
40	0.0048	0	0.25	0	0.5543
50	0	0	0	0	0.4099

Friendly Submarine Acoustic Sensor Capabilities					
Range (KM)	SSN Passive Sonar Vs. Enemy Destroyer (Pd)	SSN Passive Sonar Vs. Enemy Submarine (Pd)	SSN Passive Sonar Vs. Enemy Active Sonar (Pd)	SSN Passive Sonar Vs. Trawling Boat (Pd)	SSN Passive Sonar Vs. Merchant (Pd)
0	1	1	1	1	1
1	1	1	1	1	1
2	0.6271	0.297	1	0.3945	1
3	0.5478	0.2017	1	0.264	1
4	0.4847	0.133	1	0.1781	1
5	0.4424	0.0965	1	0.1305	1
6	0.4045	0.0676	1	0.0885	0.9994
7	0.3662	0.0454	1	0.0628	0.9953
8	0.3301	0.0286	1	0.0417	0.9883
9	0.3036	0.0187	1	0.0276	0.9837
10	0.2782	0.0117	1	0.0179	0.9755
11	0.2464	0.0057	1	0.0099	0.9623
12	0.2219	0.0023	1	0.0046	0.9543
13	0.2002	0.001	1	0.0018	0.9404
14	0.1713	0	1	0	0.9211
15	0.1592	0	1	0	0.913
16	0.1365	0	1	0	0.8931
17	0.1251	0	1	0	0.8931
18	0.1069	0	1	0	0.8593
19	0.0967	0	1	0	0.8479
20	0.0792	0	1	0	0.8259
30	0.0718	0	0.5	0	0.8166
40	0.007	0	0.25	0	0.6483
50	0	0	0	0	0.5084

Friendly Submarine and UUV ESM Sensor Capabilities				
Range (KM)	**SSN ESM Vs. Enemy Destroyer (Pd)**	**SSN ESM Vs. Enemy Land Based Radar or Communications (Pd)**	**UUV ESM Vs. Enemy Destroyer (Pd)**	**UUV ESM Vs. Enemy Land Based Radar or Communications (Pd)**
0	1	1	1	1
1	1	1	1	1
2	1	1	1	1
3	1	1	1	1
4	1	1	1	1
5	1	1	1	1
6	1	1	1	1
7	1	1	1	1
8	1	1	1	1
9	1	1	1	1
10	1	1	1	1
11	1	1	1	1
12	1	1	1	1
13	1	1	1	1
14	1	1	1	1
15	1	1	1	1
16	1	1	1	1
17	1	1	1	1
18	1	1	1	1
19	1	1	1	1
20	1	1	1	1
30	1	1	0.5	1
40	0	1	0	1
50	0	1	0	1

Enemy Surface Radar Sensor Capabilities				
Range (KM)	Enemy Destroyer Vs. SSN (Pd)	Enemy Destroyer Vs. UUV (Pd)	Enemy Land Based Radar Vs. SSN (Pd)	Enemy Land Based Radar Vs. UUV (Pd)
0	0.45	0.45	0.1	0.1
1	0.45	0.45	0.1	0.1
2	0.45	0.45	0.1	0.1
3	0.45	0.45	0.1	0.1
4	0.45	0.45	0.1	0.1
5	0.45	0.45	0.1	0.1
6	0.45	0.45	0.1	0.1
7	0.45	0.45	0.1	0.1
8	0.45	0.45	0.1	0.1
9	0.45	0.45	0.1	0.1
10	0.45	0.45	0.1	0.1
11	0.45	0.45	0.1	0.1
12	0.45	0.45	0.1	0.1
13	0.45	0.45	0.1	0.1
14	0.45	0.45	0.1	0.1
15	0.45	0.45	0.1	0.1
16	0.45	0.45	0.1	0.1
17	0.45	0.45	0.1	0.1
18	0.45	0.45	0.1	0.1
19	0.45	0.45	0.1	0.1
20	0.45	0.45	0.1	0.1
25	0.45	0	0.1	0.1
30	0	0	0.1	0.1
35	0	0	0	0

C. KINEMATIC PROBABILITY OF KILL TABLES

		UUV Probabilities of Kill		
		Threat Submarine	Threat Surface	Merchant
Range (Meters)	0	0.603	0.603	0.9
	1000	0.603	0.603	0.9
	2000	0.603	0.603	0.9
	3000	0.603	0.603	0.9
	4000	0.603	0.3326	0.9
	5000	0.603	0.0441	0.9
	6000	0.1954	0	0.9
	7000	0	0	0.7992
	8000	0	0	0.7507
	9000	0	0	0.649
	10000	0	0	0.545
	11000	0	0	0.4523
	12000	0	0	0.3528
	13000	0	0	0.2466
	14000	0	0	0.15201
	15000	0	0	0.0517
	16000	0	0	0

		Friendly Sub Probabilities of Kill		
		Threat Submarine	**Threat Surface**	**Merchant**
Range (Meters)	0	0.603	0.603	0.9
	15000	0.603	0.603	0.9
	16000	0.603	0.603	0.9
	17000	0.603	0.603	0.9
	18000	0.603	0.5458	0.9
	19000	0.603	0.1628	0.9
	20000	0.603	0	0.9
	21000	0.603	0	0.9
	22000	0.603	0	0.9
	23000	0.603	0	0.9
	24000	0.603	0	0.9
	25000	0.603	0	0.9
	26000	0.5379	0	0.9
	27000	0.0385	0	0.8529
	28000	0	0	0.8489
	29000	0	0	0.8022
	30000	0	0	0.7557
	40000	0	0	0.3963
	50000	0	0	0

		Threat Probabilities of Kill					
		Threat Submarine		Threat Surface		Threat Maritime Patrol	
		UUV	Submarine	UUV	Submarine	UUV	Submarine
Range (Meters)	0	0.765	0.603	0.765	0.603	0.765	0.603
	1000	0.765	0.603	0.765	0.603	0.765	0.603
	2000	0.765	0.603	0.765	0.603	0.765	0.603
	3000	0.765	0.603	0.765	0.603	0.765	0.603
	4000	0.765	0.603	0.765	0.603	0.765	0.603
	5000	0.765	0.603	0.765	0.4267	0.765	0.4267
	6000	0.765	0.603	0.765	0.0352	0.765	0.0352
	7000	0.765	0.603	0.765	0	0.765	0
	8000	0.765	0.603	0.765	0	0.765	0
	9000	0.765	0.603	0.765	0	0.765	0
	10000	0.765	0.603	0.1715	0	0.1715	0
	11000	0.765	0.603	0	0	0	0
	12000	0.765	0.603	0	0	0	0
	13000	0.765	0.603	0	0	0	0
	14000	0.765	0.603	0	0	0	0
	15000	0.765	0.603	0	0	0	0
	16000	0.765	0.603	0	0	0	0
	17000	0.765	0.603	0	0	0	0
	18000	0.765	0.603	0	0	0	0
	19000	0.765	0.603	0	0	0	0
	20000	0.765	0.603	0	0	0	0
	21000	0.765	0.60257	0	0	0	0
	22000	0.765	0.2313	0	0	0	0
	23000	0.765	0.0003	0	0	0	0
	24000	0.765	0	0	0	0	0
	25000	0.765	0	0	0	0	0
	26000	0.765	0	0	0	0	0
	27000	0.765	0	0	0	0	0
	28000	0.765	0	0	0	0	0
	29000	0.765	0	0	0	0	0
	30000	0.765	0	0	0	0	0
	31000	0.765	0	0	0	0	0
	32000	0.765	0	0	0	0	0
	33000	0.765	0	0	0	0	0

		Threat Probabilities of Kill					
		Threat Submarine		Threat Surface		Threat Maritime Patrol	
		UUV	Submarine	UUV	Submarine	UUV	Submarine
	34000	0.765	0	0	0	0	0
	35000	0.0516	0	0	0	0	0
	36000	0	0	0	0	0	0

D. MODELED ENTITY BEHAVIOR TABLE

Unit	Behavior State Name	Behavior	Time Length (Seconds)
Friendly Attack Submarine	Passive Search	Transit Search - Transit from waypoint to waypoint with a positive attraction towards enemy units.	Indefinite
	Shot at	Increase speed to 25 knots, avoid all enemy contacts.	1350
	Periscope Depth	Transit Search- Proceed from waypoint to waypoint with a positive attraction toward enemy units. No active transmissions. ESM sensor is enabled	60
	Fully Submerged	Transit Search- Proceed from waypoint to waypoint with a positive attraction toward enemy units. No active transmissions.	3240

Unit	Behavior State Name	Behavior	Time Length (Seconds)
Friendly ISR Submarine	Conduct ISR - Periscope Depth	Transit - Conduct ISR along defined transit path.	800
	Fully Submerged	Transit - Proceed from waypoint to waypoint along defined transit path.	200
	Shot at	Increase speed to 25 knots, avoid all enemy contacts.	1350
Common UUV	Passive Search	Transit Search- Proceed from waypoint to waypoint with a positive attraction toward enemy units. No active transmissions.	Indefinite
	Shot at	Increase speed to 8 knots, avoid all enemy contacts.	1350
	Variable Speed Avoidance	Increase speed to 8 knots to avoid merchants and trawlers.	360
	Fuel Out	UUV is lost.	Indefinite
Attack UUV	Periscope Depth	Transit Search- Proceed from waypoint to waypoint with a positive attraction toward enemy units. No active transmissions. ESM sensor is enabled	60

Unit	Behavior State Name	Behavior	Time Length (Seconds)
	Fully Submerged	Transit Search- Proceed from waypoint to waypoint with a positive attraction toward enemy units. No active transmissions.	3240
	Post Attack	Transit - Proceed from waypoint to waypoint avoiding enemy contact. No active transmissions	Indefinite
	21” Attack UUV Terminal Phase	Once contact is made with an enemy surface combatants or enemy submarine increase speed to 25 knots and intercept hostile vessel.	Indefinite
	Glider Attack UUV Terminal Phase	Once contact is made with an enemy surface combatants or enemy submarine increase speed to 15 knots and intercept hostile vessel.	Indefinite
ISR UUV	Passive Search	Transit - Proceed from waypoint to waypoint avoiding enemy contact. No active transmissions	3240
	Conduct ISR - Periscope Depth	Transit - Conduct ISR along defined transit path.	800

Unit	Behavior State Name	Behavior	Time Length (Seconds)
	Fully Submerged	Transit - Proceed from waypoint to waypoint along defined transit path.	200
IO UUV	Deceive - Profile 1	Transit - Proceed from waypoint to waypoint avoiding enemy contact. Active acoustic and radio frequency emissions.	Indefinite
	Deceive - Profile 2A	Transit - Proceed from waypoint to waypoint avoiding enemy contact. Active acoustic and radio frequency emissions.	720
	Deceive - Profile 2B	Transit - Proceed from waypoint to waypoint avoiding enemy contact.	1800
Enemy Submarine	Passive Search	Random movement with average path length of 10,000 meters. Passive sonar utilized.	1600
	Active Search	Random movement with average path length of 10,000 meters. Active sonar utilized.	180
	Organic Enemy Contact	If passive move away from enemy if within 100,000 meters. If active move towards enemy if within 100,000 meters.	Indefinite

Unit	Behavior State Name	Behavior	Time Length (Seconds)
	Inorganic Enemy Contact	If passive move away from enemy if within 30,000 meters. If active move towards enemy if within 30,000 meters.	Indefinite
	Shot At	Increase speed to 18 knots. Avoid all enemies and friends.	1350
Enemy Destroyer	Passive Search	Random movement with average path length of 10,000 meters. Passive sonar utilized.	1800
	Active Search	Random movement with average path length of 10,000 meters. Active sonar utilized.	120
	Organic Enemy Contact	If passive move away from enemy if within 100,000 meters. If active move towards enemy if within 100,000 meters.	Indefinite
	Inorganic Enemy Contact	If passive move away from enemy if within 30,000 meters. If active move towards enemy if within 30000 meters.	Indefinite
	Shot At	Increase speed to 30 knots. Avoid all enemies and friends.	1350
Enemy	Search	Conduct ladder search.	Indefinite

Unit	Behavior State Name	Behavior	Time Length (Seconds)
Maritime Patrol	Organic Enemy Contact	Aggressive pursue enemy.	Indefinite
	Inorganic Enemy Contact	Aggressive pursue enemy.	600
Enemy Helo	Search	Conduct ladder search.	Indefinite
	Organic Enemy Contact	Aggressive pursue enemy.	Indefinite
	Inorganic Enemy Contact	Aggressive pursue enemy.	600
Trawler	Trawling	Random movement with average path length of 10,000 meters.	Indefinite
Merchant	Transit	Movement along a defined shipping lane with average path length of 50,000 meters with a shipping lane width of 60,000 meters.	Indefinite

APPENDIX D: REQUIREMENTS ANALYSIS

The goal of deriving requirements is to determine several critical system characteristics that are applicable to the scoped mission areas. Modeling and simulation efforts are utilized to analyze relevant requirements, which in turn provide significant insights for the analysis of alternatives.

Approaching system requirements from both a functionally derived perspective and by determining critical operational issues (COIs), results in a more comprehensive requirements analysis. Furthermore, by using two different approaches, requirements were captured that would have otherwise been overlooked.

This analysis presents a top-level set of notional requirements, which are used to evaluate potential alternatives. It is important to note that these requirements are not intended to be used as “design-to” technical specifications and requirements. It is expected that as solutions are developed more technical requirements will be determined based on the resultant designs, technology constraints, and additional in-depth analysis of particular mission areas.

E. FUNCTIONALLY DERIVED REQUIREMENTS ANALYSIS

Each primary sub-function defined in Chapter IV is analyzed for applicable measures of performance (MOP). Notional minimum, maximum, and goal parameters of each MOP are determined in order to quantify the functions and aid in system requirement development. MOPs included in Table D-1 are based on multiple factors including: expected mission time requirements, current technology available, analogy with respect to other systems of record, and operational experience of SEA-19A team members.

Table D-1: Functionally Derived MOPs

Function	Sub-function /Units	MOP	Min / Max / Goal
Navigate N.1	**Launch** (% Successful force launch time)	Successful launch of force from homeport within 72 hours of call up	**Min:** 90% time requirement met **Max:** 100% time requirement met **Goal:** 100% time requirement met
N.2	(% Successful vehicle launch time)	Successful launch of vehicle from launch platform within 2 hours of execution order	**Min:** 90% time requirement met **Max:** 100% time requirement met **Goal:** 100% time requirement met
N.3	**Maneuver** (% Successful transit to OPAREA)	Force/vehicles that successfully reach OPAREA	**Min:** 98% of force/vehicles arrive to OPAREA **Max:** 100% of force/vehicles arrive to OPAREA **Goal:** 100% of force/vehicles arrive to OPAREA
N.4	(% vehicle losses due to obstacles)	Vehicles lost due to environmental obstacles	**Min:** 1% of vehicles allowed to be lost **Max:** 0% of vehicles allowed to be lost **Goal:** 0% of vehicles allowed to be lost
N.5	(% force in OPAREA time requirement)	Successful deployment of force/vehicle to OPAREA within 10 days of call up	**Min:** 95% time requirement met **Max:** 100% time requirement met **Goal:** 100% time requirement met
N.6	**Recover** (% Returned to point of origin)	Non-disposable vehicles launched that successfully return to launch platform	**Min:** 98% vehicles return **Max:** 100% vehicles return **Goal:** 100% vehicles return
N.7	(% Disposable vehicles	Disposable vehicles launched that are	**Min:** 99% vehicles destroyed **Max:** 100% vehicles

Function	Sub-function /Units	MOP	Min / Max / Goal
	completely destroyed)	successfully destroyed and/or scuttled to point of not compromising OPSEC	destroyed **Goal:** 100% vehicles destroyed
Sense S.1	**Sense Self** (% Time water intrusion detected vehicle)	Successfully detecting water intrusion of vehicle	**Min:** 99% time successful detection **Max:** 100% time successful detection **Goal:** 100% time successful detection
S.2	(Geospatial accuracy in meters)	Force/vehicle location accuracy in meters	**Min:** 0 meters **Max:** 2 meters **Goal:** <1 meter
S.3	(% Self-diagnostic runtime errors)	Runtime errors detected during self-diagnostic testing of vehicle	**Min:** 0% **Max:** 1% **Goal:** 0%
S.4	(Depth accuracy in meters)	Vehicle depth accuracy in meters	**Min:** 0 meters **Max:** 3 meters **Goal:** <3 meters
S.5	(Speed accuracy in knots)	Vehicle speed through water accuracy in knots	**Min:** 0 kts **Max**: 2 kts **Goal:** <1 kts
S.6	**Sense Contact** (Geospatial accuracy in meters)	Contact location accuracy in meters	**Min:** 0 meters **Max:** 20 meters **Goal:** <10 meters
S.7	(Relative geospatial accuracy in meters)	Contact geospatial location relative to vehicle in meters	**Min:** 0 meters **Max:** 10 meters **Goal:** <5 meters
S.8	(Depth accuracy in meters)	Submerged contact depth accuracy in meters	**Min:** 0 meters **Max:** 10 meters **Goal:** <5 meters
S.9	(Relative depth accuracy in meters)	Submerged contact depth relative to vehicle in meters	**Min:** 0 meters **Max:** 10 meters **Goal:** <5 meters

Function	Sub-function /Units	MOP	Min / Max / Goal
S.10 S.11	(Speed accuracy in knots) (Relative speed accuracy in knots)	Contact speed through water in knots Contact speed relative to vehicle in knots	**Min:** 0 kts **Max**: 2 kts **Goal:** <1 kts **Min:** 0 kts **Max**: 2 kts **Goal:** <1kts
  S.12 S.13 S.14 S.15	**Sense Environment** (Temperature accuracy in F) (Salinity accuracy SSU) (Pressure accuracy in kg/m^3) (Current accuracy in knots)	 Ambient temperature accuracy in degrees F Salinity accuracy in standard units Pressure accuracy in kg/m^3 Environmental flow accuracy in knots	 **Min:** 0F **Max:** 2F **Goal:** <1F **Min:** 0 **Max:** .5 **Goal:** <.3 **Min:** 0 kg/m^3 **Max**: 1 kg/m^3 **Goal:** <1kg/m^3 **Min:** 0 kts **Max**: 2 kts **Goal:** <1 kts
Communicate C.1 C.2	**Send Data** (Communications latency in time units) (Communications latency in time units)	 Time it takes transmitted data to reach receiving platform per packet (Air) Time it takes transmitted data to reach receiving platform per packet (Undersea)	 **Min:** 1 ns **Max:** 2 min **Goal:** <15 sec **Min:** 1 ns **Max**: 10 min **Goal:** <1 min
C.3	**Receive Data** (Decryption rate in time units)	 Rate at which encrypted data received is decrypted per packet for further processing	 **Min:** 1 ns **Max:** 5 sec **Goal:** 1 ms
Command and Control C2.1	**Store Data** (Onboard ROM in	 Read-only memory on	 **Min:** 500GB

Function	Sub-function /Units	MOP	Min / Max / Goal
	bytes)	vehicle in bytes	**Max**: Industry Limited **Goal:** 1.0TB
	Perform Specific Task		
C2.2	(ISR surveillance time in hours)	Total HD video/audio monitoring time during ISR mission (vehicle)	**Min:** 24 hours **Max:** 144 hours **Goal:** 72 hours
C2.3	(Decoy noise time in hours)	Continuous time vehicle can emit decoy acoustics/EM radiation	**Min:** .5 hours **Max:** 72 hours **Goal:** 24 hours
C2.4	(Mine identification rate in #mines/hour)	During mine hunting mission the rate at which vehicle finds and identifies mines in a known minefield	**Min:** 1/hour **Max:** none **Goal:** 5/hour
C2.5	(Mine neutralization rate in #mines/hour)	The number of identified mines neutralized by a vehicle per hour	**Min:** 1/hour **Max:** none **Goal:** 2/hour
C2.6	(Mine laying capacity in #mines/sortie)	The number of mines vehicle can lay during one sortie	**Min:** 3/sortie **Max:** Dependent on platform size **Goal:** 6/sortie
C2.7	(EM interception capacity in hours)	Total hours of EM radiation intercepted by vehicle in hours per mission	**Min:** 24 hours **Max:** 144 hours **Goal:** 72 hours
C2.8	(Probability of hit for weapons release in %)	(Probability that enemy asset is hit when vehicle launches munitions)	**Min:** 60% **Max:** 100% **Goal:** 95%
	Process Data		
C2.9	(RAM in bytes)	Random access memory on vehicle necessary to perform all mission areas	**Min:** 128GB **Max**: Industry Limited **Goal:** 512GB
C2.10	(Total CPU time processing	Time it takes for CPU to process instruction	**Min:** none **Max:** 1 sec

Function	Sub-function /Units	MOP	Min / Max / Goal
	latency in time units)	in CPU time (i.e., not elapsed time)	**Goal:** <.05 sec
Provide Support PS.1	**Equip** (Vehicular operational availability in %)	The percentage of time each vehicle is available during total force operating time	**Min:** 80% **Max:** 100% **Goal**: 95%
PS.2	(Maximum vehicular preventative maintenance time in hours)	The maximum time a vehicle requires for preventative maintenance when all required equipment is available for maintenance	**Min:** none **Max:** 8 hours **Goal**: 4 hours
PS.3	**Man** (Number of operating personnel per vehicle)	The total number of operators required to operate a single vehicle	**Min:** 1 **Max**: 3 **Goal:** <3
PS.4	**Train** (Ratio of trained operators to number of vehicles in UUV force)	The ratio of trained operators to the number of UUVs in the force	**Min:** 2/1 **Max:** none **Goal**: 4/1

F. CRITICAL OPERATIONAL ISSUE REQUIREMENT ANALYSIS

The mission analysis performed in Chapter V CONOPS identified several initial critical measures of effectiveness (MOEs) of UUV systems. MOEs provide a way to measure the extent that a system accomplishes or supports a particular mission or task. Important UUV system MOEs include, but are not limited to:

Host Platform Survivability

UUV Survivability

UUV Endurance Capability

UUV Signal Detection Capability

UUV Signal Classification Capability

UUV Reliability

UUV Transportability

UUV Interoperability

UUV Maintainability

UUV Modularity

These initial system MOEs are used in conjunction with functional analysis, mission analysis, and initial capabilities assessment to determining COIs. COIs are defined by their relevancy to the mission, the importance to mission accomplishment, and the risk of not achieving mission objectives (Hoivik 2013). As shown in Table D-2, UUV system COIs are often represented in the form of a question related to the problem at hand.

Table D-2: Critical Operational Issues Derived From CONOPS Analysis

COI	Issue	Question
1	Endurance	Is the endurance capability of the UUV sufficient for mission accomplishment?
2	Mobility	Is the mobility of the UUV sufficient to support accomplishing the mission with regards to speed, reaction time, and obstacle avoidance?
3	Autonomy	Does the UUV have sufficient autonomous capabilities to accomplish the mission without the need for human control once launched from the host platform?
4	Transportability	Does the UUV have the capability to be transported, launched, and recovered from multiple U.S. Navy platforms?
5	Compatibility	Is the compatibility of modular components and the UUV sufficient to provide mission flexibility?
6	Lethality	Is the lethality of the UUV lethal payload packages sufficient for mission accomplishment?
7	Interoperability	Are communication capabilities of the UUV sufficient for mission accomplishment?
8	Command and Control (C2)	Are the command and control capabilities of the UUV sufficient for mission accomplishment?
9	Sensor Effectiveness	Are the sensor capabilities of the UUV sufficient for mission accomplishment?
10	Employment	Are behavior patterns developed through software for the UUV effective in mission accomplishment?
11	Human Systems Integration	Are users aboard the host platform able to fully utilize the capabilities of the UUV?
12	Survivability	Is the survivability of the UUV satisfactory for operations in various maritime threat environments?

Identification of COIs led to the development of more detailed MOEs and MOPs. MOEs address specific COIs and MOPs provide a quantitative or qualitative measure of the system's MOEs. It should be noted that unlike the functional requirement analysis method, the COI method does not include notional quantitative values for MOPs.

- **COI 1 - Endurance**
  - MOE 1.1 Capability to operate for XX time
    - MOP 1.1.1 Proportion of power for mission profile
    - MOP 1.1.2 Fuel consumption rate
    - MOP 1.1.3 Battery discharge rate
  - MOE 1.2 Recharge capability
    - MOP 1.2.1 Battery recharge rate
  - MOE 1.3 Energy storage capability
    - MOP 1.3.1 Average battery storage capacity
    - MOP 1.3.2 Fuel storage capacity
- **COI 2 - Mobility**
  - MOE 2.1 Navigation capability
    - MOP 2.1.1 Proportion of detected obstacles
    - MOP 2.1.2 Average location error
    - MOP 2.1.3 Average error for self-location
  - MOE 2.2 Maneuvering capability
    - MOP 2.2.1 Rate of speed
    - MOP 2.2.2 Average speed for sea conditions
    - MOP 2.2.3 Rate of ascent/descent
- **COI 3 - Autonomy**
  - MOE 3.1 Autonomous operations capability

        - MOP 3.1.1 Proportion of data elements transmitted correctly. The ratio of the total number of data elements transmitted correctly to the total number of data elements entered for a specific task.
        - MOP 3.1.2 Proportion of tasks completed using UUV automated systems to the total number of tasks attempted by UUV automated systems
        - MOP 3.1.3 Proportion of problems resolved by UUV internal systems. The ratio of the total number of problems solved by the UUV internal systems to the total number of problems identified by the UUV internal systems.

- **COI 4 - Transportability**
    - MOE 4.1 Capability to be launched and recovered by current U.S. Navy platforms
        - MOP 4.1.1 Proportion of existing U.S. Navy platforms capable of being launched/recovered from
    - MOE 4.2 Capability to be transported by current U.S. Navy platforms
        - MOP 4.2.1 Proportion of existing U.S. Navy platforms capable of being transported by
- **COI 5 – Compatibility**
    - MOE 12.1 Compatibility of different sensors
        - MOP 12.1.1 Proportion of sensors compatible with the UUV
    - MOE 12.2 Compatibility of batteries
        - MOP 12.2.1 Proportion of battery types compatible with the UUV
- **COI 6 - Lethality**
    - MOE 6.1 Engagement timeliness effectiveness
        - MOP 6.1.1 Average time from target acquisition to engagement

- Moe 6.2 Weapons effect
    - MOP 6.2.1 Proportion of target engagements vs. acquisitions
    - MOP 6.2.2 Probability of kill (P_k)
    - MOP 6.2.2 Average hit range
    - MOP 6.2.3 Loss exchange ratio
    - MOP 6.2.4 System exchange ratio
    - MOP 6.2.5 Force exchange ratio

- **COI 7 - Interoperability**
  - MOE 7.1 Atmospheric link capability
    - MOP 7.1.1 Average signal range
    - MOP 7.1.2 Average data rate
  - MOE 7.2 Receiving capability
    - MOP 7.2.1 Proportion of uninterrupted communications
    - MOP 7.2.2 Message accuracy
  - MOE 7.3 Transmission capability
    - MOP 7.2.1 Average data message completion time (MCT)
    - MOP 7.2.2 Average transmission backlog
- **COI 8 - Command and Control (C2)**
  - MOE 8.1 Commander’s requirement management
    - MOP 8.1.1 Proportion of intelligence requirements satisfied
    - MOP 8.1.2 Proportion of tasking successes
  - MOE 8.2 Situation development
    - MOP 8.2.1 Proportion of mines reported
    - MOP 8.2.2 Average time to generate safe Q-route

- **COI 9 – Sensor Effectiveness**
    - MOE 9.1 Target search capability
        - MOP 9.1.1 Target search rate
    - MOE 9.2 Target detection
        - MOP 9.2.1 Proportion of detections
        - MOP 9.2.2 Average range of detection
    - MOE 9.3 Target recognition
        - MOP 9.3.1 Time from detection from recognition
        - MOP 9.3.2 Proportion of identifications vs. recognitions
        - MOP 9.3.3 Proportion of correct recognitions
- **COI 10 – Employment**
    - MOE 10.1 Target development
        - MOP 10.1.1 Proportion of High Payoff Targets
    - MOE 10.2 Search coverage efficiency
        - MOP 10.2.1 Proportion of planned area successful y searched per mission
            - DR 10.2.1.1 Square nautical miles of planned area successfully searched
            - DR10.2.1.2 Square nautical miles of planned area
        - MOP 10.2.2 Proportion of planned area searched multiple times
- **COI 11 - Human Systems Integration**
    - MOE 11.1 System task performance
        - MOP 11.1.1 The average time required to successively plan and load a mission package

        - MOP 11.1.2 The average usability ratings of system critical tasks: The average ratings of system critical task characteristics given by test players at the end of each task trial, based on the ease-of-use
    - MOE 11.2 Safety hazards
        - MOP 11.2.1 The proportion of trials where safety/hazard related incidents occur: The ratio of the total number of trials where safety related or hazardous incidents occur to the total number of trial
        - MOP 11.2.2 The average interface usability ratings: The average ratings for each interaction category of various characteristics of human-machine interfaces rendered by the test players at the completion of the test
- **COI 12 - Survivability**
    - MOE 12.1 Detection avoidance
        - MOP 12.1.1 Detection avoidance proportion
        - MOP 12.1.2 Detection survivability ratio
    - MOE 12.2 Situation awareness capability
        - MOP 12.2.1 Threat false alarm rate
            - DR 12.2.1.1 Number of alarms
            - DR 12.2.1.2 Number of false threats
        - MOP 12.2.2 Average system response time
    - MOE 12.3 Acquisition avoidance
        - MOP 12.3.1 Average expose time
        - MOP 12.3.2 Acquisition avoidance proportion

G. CONSOLIDATED UUV SYSTEM REQUIREMENTS

Using both methods described in this chapter, an initial set of system requirements is established. To provide traceability to the function analysis, the requirements are organized in regards to the functions that the system must care out.

Navigate Requirements:

N.1 The entire force needed to complete UUV supported missions must be deployable within 72 hours 98±2% of the time when ordered. Accuracy will be measured by the ratio of deployments conducted in less than 72 hours to total deployments requested.

N.2 UUVs must have successful launch from launch platform within 2 hours of execution order 98±2% of the time. Accuracy will be measured by the ratio of sorties conducted in less than 2 hours to total sorties requested.

N.3 In the case of total force movement, the entire force must make it to the OPAREA 98% of the time at a minimum. In the case of individual UUV mission deployment, the UUV must make it to the mission space at least 98% of the time.

N.4 UUV losses per 100 sorties should not exceed one vehicle due to environmental obstacles to include fishing nets, landforms and currents. This does not include losses due to enemy combatants, UUV system failure or UUVs pre-programmed to self-destruct.

N.5 In addition to meeting the 72 hour deployment requirement, the force including the UUVs required for the mission must be able to be on station within 10 days of call up. This assumes forces called up will be the closest regional forces to the OPAREA.

N.6 For non-disposable UUVs, a maximum of two UUVs can be lost per 100 sorties. This includes losses for all reasons except for UUVs pre-programmed to self-destruct.

N.7 For disposable UUVs, only up to one UUV can fail to self-destruct or scuttle in deep ocean for every 100 self-destruct orders given. Design should attempt to ensure zero failures of execution of self-destruct orders.

Sense Requirements:

S.1 UUV should be designed to detect water intrusion of its pressure hull. Design testing should meet 99% success rate at detecting water intrusion at operational depths. UUV should be pre-programmed to self-destruct if water intrusion levels endanger further UUV operation.

S.2 UUV force including support platforms must meet accuracy of less than 20 meters off geospatially when considering own vehicle/platform. Goal should be to achieve minimal deviation from actual geospatial position.

S.3 UUV shall be programmed to run periodic and prompted self-diagnostic tests. The programming should be robust enough that during design testing the system shall not experience run-time errors more than 1% of the time self-diagnostics are run.

S.4 UUV self-depth accuracy shall be resolved to an accuracy of less than 10 meters with a goal to achieve minimal deviation from actual depth.

S.5 UUV speed accuracy shall be resolved to an accuracy of less than 2 knots from actual speed through water with a goal to achieve minimal deviation from actual speed through water.

S.6 Due to fire control considerations, sensed contacts from the UUV shall meet accuracy of less than 20 meters off geospatially with a goal of minimal deviation from actual geospatial position.

S.7 In addition to actual geospatial positioning, due to evasion and fire control considerations, the UUV shall meet accuracy of less than 10 meters off relative geospatial position to the sensed contact.

S.8 Due to fire control considerations sensed submerged contacts from the UUV shall meet accuracy of less than 10 meters off of actual depth with a goal of minimal deviation from actual depth.

S.9 In addition to actual contact depth, due to evasion and fire control considerations, the UUV shall meet accuracy of less than 10 meters off relative depth to the sensed contact.

S.10 Due to fire control considerations sensed contacts from the UUV shall meet accuracy of less than 2 knots speed through water off of actual contact speed with a goal of minimal deviation from actual speed through water.

S.11 In addition to actual contact speed through water, due to evasion and fire control considerations, the UUV shall meet accuracy of less than 2 knots off relative speed through water against sensed contact.

S.12 UUV shall resolve environmental temperature to an accuracy of less than 2F from actual environmental temperature and shall be designed to operate well outside of global oceanographic temperature extreme averages.

S.13 Due to acoustic detection range considerations, UUV must be able to resolve salinity to at least .5 standard salinity units.

S.14 Due to water intrusion considerations, the UUV should be able to resolve external hull pressure to at least 1kg/m3.

S.15 In order to determine geospatial speed, the UUV should be able to resolve external current speed to within 2 knots of actual current speed.

Communicate Requirements:

C.1 Data transmitted above the surface of the water from UUV shall have a transmitted latency to intended receiving station not to exceed 2 minutes per packet of data with a goal of <15 seconds to meet projected worst-case mission time sensitivity.

C.2 Data transmitted undersea from the UUV shall have a transmitted latency to intended receiving station not to exceed 10 minutes per packet of data with a goal of <1 minute to meet projected worst-case mission time sensitivity.

C.3 For communications between UUVs and force platforms, any encrypted data received on either end shall meet a maximum decryption speed of <5 seconds per packet of data with a goal of <1 millisecond.

Command and Control Requirements:

C2.1 UUVs designed for ISR shall have a minimum of 500GB onboard read-only memory to allow for at least 24 hours of continuous HD (720p) video recording capability with audio. The UUV should be designed to have the ability to convert to a lower resolution and/or audio only and EM data recording if so desired by mission planners.

C2.2 UUVs shall meet a minimum capability of 24 hours of continuous HD video recording capability with audio with a goal of 72 hours of continuous monitoring. Due to current projected onboard power limitations, maximum continuous HD video monitoring should be capped to 144 hours.

C2.3 UUVs performing decoy missions shall produce a continuous decoy signal for a minimum of half an hour while maneuvering at a speed of up to 5 knots with a goal of 24 hours of continuous signal.

C2.4 UUVs performing mine hunting missions in a known mine location shall identify and locate at least one mine per hour of mine hunting operation with a goal of five mines per hour.

C2.5 UUVs performing mine neutralization missions in a known mine location shall neutralize at least one mine per hour of mine neutralization operation with a goal of two mines per hour.

C2.6 UUVs performing mine laying missions shall meet a minimum requirement of laying three mines per mine laying sortie to justify use of UUVs in lieu of other platforms due to mine laying capacity projected by surface vessels.

C2.7 In addition to optical/audible monitoring requirements, UUVs shall meet a minimum capability of 24 hours of continuous EM radiation monitoring with a goal of 72 hours of continuous EM radiation monitoring.

C2.8 UUVs performing attack missions must test to a probability of hit of at least 60% if weapons solution has been determined organic to the UUV (i.e., weapons solution not determined by operator).

C2.9 UUV must have minimum of 128GB of random access memory onboard to ensure enough memory available to meet any future requirements as more complex processing requirements evolve due to programming improvements.

C2.10 UUV CPU time latency, not elapsed time which includes user time and instruction wait time, shall achieve a maximum lag of 1 second.

Provide Support Requirements:

PS.1 UUV operational availability shall exceed 80% with a goal of 95%. This is based on UUVs deployed with an operational force underway and does not include UUVs attached to forces in port.

PS.2 UUVs shall be designed to allow for completion of the most complex preventative maintenance item in less than 8 real time hours with a goal of 4 hours. Man-hours may exceed 8 hours.

PS.3 UUVs shall be designed such that a maximum of 3 operators are needed to operate the UUV for any mission set with a goal of a single operator.

PS.4 Manning for the UUV force shall ensure at least two trained operators exist for every UUV in the fleet with a goal of four trained operators.

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APPENDIX E: COORDINATED SENSING MODELING

A. COORDINATED SENSING INTRODUCTION

The UUV Master Plan identified intelligence, surveillance, and reconnaissance (ISR) as the top priority mission area for unmanned undersea vehicles (UUVs) (UUV Master Plan 2004). To better inform our analysis of alternatives for the appropriate employment and vehicle selection for this mission, various modeling tools are used to develop an understanding of the relevant parameters for consideration in the analysis. We discuss, in the following sections, the design and results of our coordinated sensing model, which investigated the specific application of UUVs in target tracking scenarios. The intent of this model is to develop a better understanding of the dependency of target resolution on various employment and vehicle design parameters.

B. COORDINATED SENSING MODEL

This section discusses the design of our coordinated sensing model for stationary and mobile tracking of a target with unmanned undersea vehicles (UUVs). The spatial arrangement of the model is introduced, and the underlying mathematical relationships for multi-vehicle sensor data fusion are briefly discussed. This model is used to understand the dependency of target position uncertainty on various vehicle and sensor parameters, including: 1) sensor bearing accuracy; 2) UUV inter-vehicle separation distance; 3) UUV speed in relation to target speed. The results of this analysis are in included in Section C.

1. MODEL DESIGN

Figure E-1 shows the two-dimensional arrangement of the target and UUVs in the model. The target is centrally placed in a xy-Cartesian coordinate system with initial position of $x=0$ and $y=y_o$. The UUVs were equally spaced along the x-axis to attain symmetry between the number of vehicles left and right of the target (for a single vehicle scenario, the UUV is placed at x=0). Whether for a static or mobile analysis, the target and vehicles maintained a constant y_o separation for all time, T, and are always in the

same plane. Additionally, UUVs maintain a constant separation distance, l, from each other and never deviate from the x-axis. While we understand vehicle employment in a real tracking scenario would likely not have this arrangement, it is used for simplicity, since the aim is only to develop a general understanding of parameter dependency in target tracking.

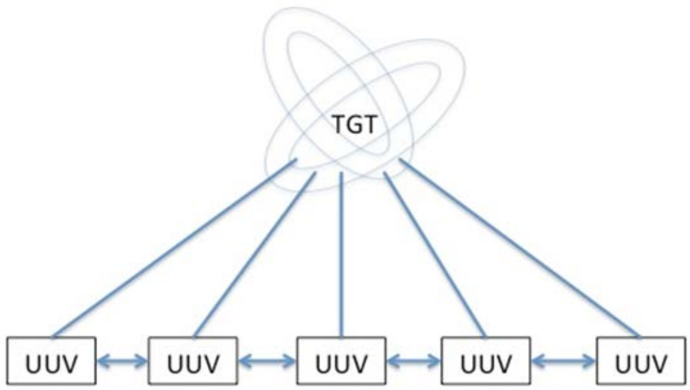

Figure E-1: Geometric relationship between target and UUVs in the model. This arrangement was used for both mobile and static analyses.

2. SENSOR MEASUREMENTS AND THE COVARIANCE INTERSECTION

Each UUV in the model took measurements of the relative bearing and range of the target, using acoustic sensors only. Measurements are assumed to be unaffected by environmental constraints and are of sufficient signal-to-noise ratio to distinguish the target from background noise. Measurements are also assumed to have some level of noise associated with them. For simplicity, noise is modeled as zero-mean, white and Gaussian. Therefore, uncertainties of the bearing (η_B) and range (η_R) measurements at each time step are defined as:

$$\eta_B = \sigma_B * randn(),$$
$$\eta_R = \sigma_R * randn(),$$

where, σ_B and $\sigma_R$were the standard deviations of the measurement distributions; $randn()$was the randomly generated Gaussian noise.

As shown in Figure E-2, the basic problem of the model is fusing these sensor measurements to yield an estimate of the target's position relative to the UUVs, while minimizing its uncertainty and maintaining consistency.

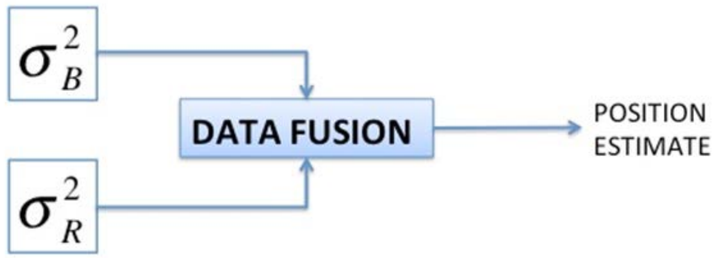

Figure E-2: Fusion of bearing and range measurements to yield an estimate of target position. σ_B^2 and σ_R^2 are the variances of the bearing and range measurement distributions, respectively.

There were different ways to do this, but the widely accepted covariance intersection algorithm (Julier and Uhlmann 1997), takes a convex combination of the sensor data variances to minimize the uncertainty in the estimated target position. Mathematically, this combination is expressed as $R_i^{-1} = w\sigma_{RR}^2 + (1-w)\sigma_{BB}^2$, where R_i^{-1} is the inverse of the covariance matrix of the i_{th} UUV given by:

$$R_i = \begin{bmatrix} \sigma_{RR}^2 & \sigma_{RB}^2 \\ \sigma_{BR}^2 & \sigma_{BB}^2 \end{bmatrix},$$

and w is a weighting factor used for different design specifications. This method builds off the observation that the ellipses formed by σ_{RB}^2 and σ_{BR}^2 are always contained within the intersection region bounded by σ_{RR}^2 and σ_{BB}^2, regardless of their values. This suggests the fused data will consistently fall within this intersection region, even without knowledge of the correlation between σ_R^2 and σ_B^2 (Julier and Uhlmann 1997). The tighter the intersection region shown in Figure E-3 becomes, the more accurate the estimation of the target position.

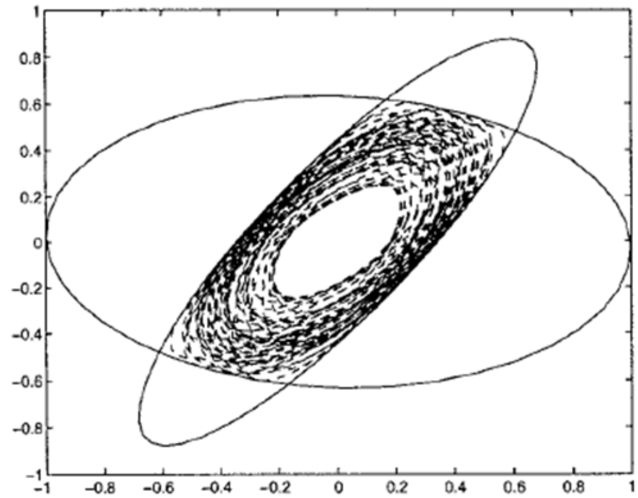

Figure E-3: The covariance intersection region. The solid-lined ellipses would represent the variances of the bearing and range measurements in our model. The dash-lined ellipses would be the estimate of the target's position. (From Julier and Uhlmann 1997)

3. DATA FUSION IN THE MODEL

To more easily apply this algorithm, sensor measurements are assumed to be uncorrelated, which means they have no dependence on each other. It is also assumed there is no spatial dependence of the range measurement, which means every vehicle has the same standard deviation in their range uncertainty regardless of distance to the target. This is done to prevent overcomplicating the model. Therefore, the covariance matrix of the i_{th} UUV in its local reference frame (i.e., bearing (θ_i) and range from itself) is given by:

$$R_i = \begin{bmatrix} \sigma_R^2 & 0 \\ 0 & \sigma_B^2 \end{bmatrix}.$$

As (Chung, Burdick, and Murray 2006) suggest, this matrix structure is consistent with the standard range-finding sensor models of (Ramachandra 2000). To transform from the local to global Cartesian reference frame, the rotation matrix provided by (Fitzgerald 1985) is applied:

$$Ti = \begin{bmatrix} \cos(\theta_i) & -\sin(\theta_i) \\ \sin(\theta_i) & \cos(\theta_i) \end{bmatrix},$$

at each time interval to give $R_{i\_global} = T_i R_i T_i^T$. Owing to the mathematical form of the covariance intersection algorithm, the fused observations of M UUVs at each time interval become:

$$P_{fused}^{-1} = \sum_{i}^{M} R_{i\_global}^{-1}.$$

For a more detailed discussion of multi-sensor data fusion, see (Bar-Shalom and Fortmann 1988).

4. COST FUNCTION

The cost function to be minimized is given by $J = tr\left(P_{fused}\right)$, where tr is the trace of the inverse fused matrix. The determinant can also be used for this purpose, but we elected the trace approach since our matrices had element values on the diagonals only. The term trace is defined as the "resolution" of the fused data. The objective, therefore, is to investigate how to improve the resolution of the target position by minimizing the cost (i.e., uncertainty).

5. SECTION SUMMARY

This section introduced the structure of our basic target-tracking model. The relevant theory for our data fusion algorithm was discussed, and the cost function defined. The assumptions made in the model, however overly simplistic, are appropriate for the level of research and did not diminish the value of the analyses conducted.

C. COORDINATED SENSING RESULTS

This section discusses the results obtained from the coordinated sensing model when applied to both static and mobile tracking scenarios. A parametric analysis is conducted to develop an understanding of the cost function dependency on various model parameters. Where appropriate, general conclusions are drawn and observations made to aid in understanding the results.

1. STATIC TRACKING

The model is first employed in a static tracking scenario, where neither the target nor the UUVs have a velocity component changing their position over time. The UUV and target separation, y_o, is 1000 meters. Two analyses are conducted—the first adjusted inter-UUV spacing while keeping sensor accuracy constant, and the second adjusted the quality of the sensor while maintaining vehicle separation constant. The results of the two analyses are shown in Figures E-4 and E-5 respectively. For clarity, sensor quality is adjusted by only varying the standard deviation of the bearing measurement. The range measurement, from the operational experience of the authors, is assumed to be difficult to vary without appropriate vehicle ranging techniques.

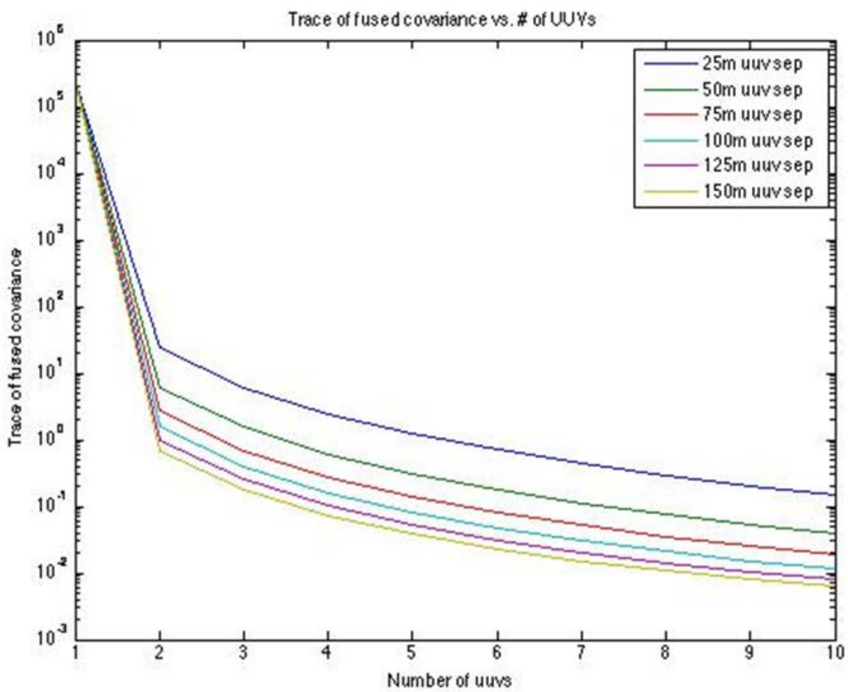

Figure E-4: Trace of fused covariance versus the number of UUVs for varying UUV separation distances. Bearing accuracy is +/-5 degrees.

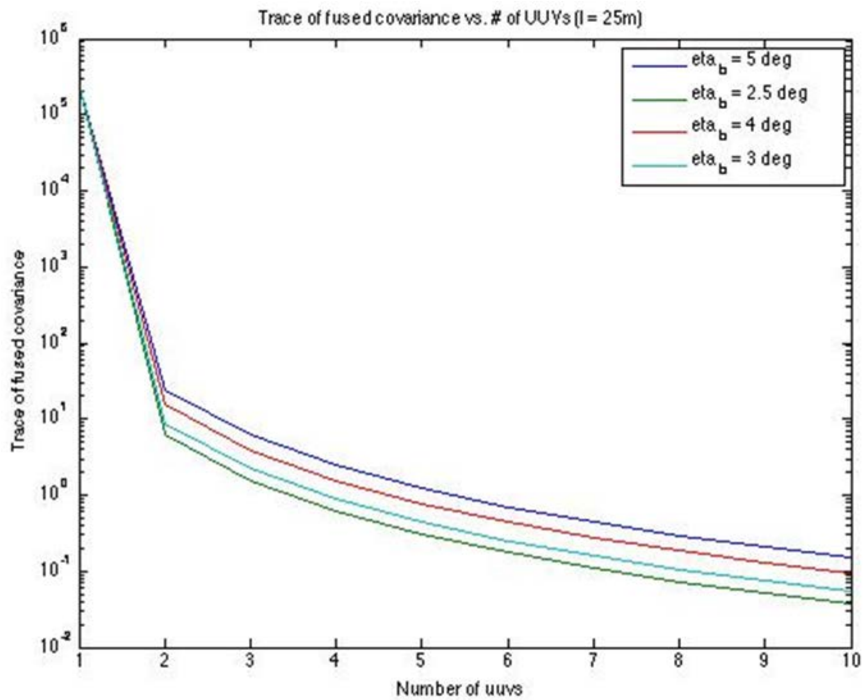

Figure E-5: Trace of fused covariance versus number of UUVs for varying sensor quality (i.e., varying standard deviation of bearing measurement). The UUV separation distance is 25m.

Figures 4 and 5 both show resolution of the target's position improving (i.e., fused covariance decreasing) with more and more UUVs added to the scenario. Intuitively, this is expected. More sensors on target provided more information to help shape the position estimate. If anything, this result indicated that the model is working as expected. The more telling results arise when looking at how the number of UUVs required for a given resolution varied with different separation distances and sensor qualities. For example, Figure 4 shows for a traced covariance of 0.7, varying the UUV separation distance from 25m to 50m reduces the number of UUVs from eight to five. For the same resolution, Figure 5 shows a reduction in the number of UUVs from seven to four for a sensor improvement of 2.5 degrees (i.e., from +/-5 degrees uncertainty to +/-2.5 degrees uncertainty). Though these two separate analyses appeared to yield similar results, it is difficult to draw any substantive conclusions by comparing them. Any attempt to do so is like comparing apples to oranges. The general conclusion is that there are two different ways to attain a desired target resolution with multiple UUVs. The first, by increasing UUV separation distance, has the advantage of using a mediocre sensor, but with greater range over which to communicate the fusion of data. This is also the cheaper option. The

second method, improving sensor quality, has the disadvantage of higher cost, but the advantage of being able to communicate between vehicles over shorter distances.

2. MOBILE TRACKING

The model is then employed in a mobile tracking scenario, where both the target and UUVs have a velocity component adding to their x-position at each time interval. To verify the model is setup properly, a test case is ran with the target having a greater velocity then the UUVs. Figure E-6 shows the target resolution degrades over time, as expected, since the target continuously opens lateral range on the vehicles.

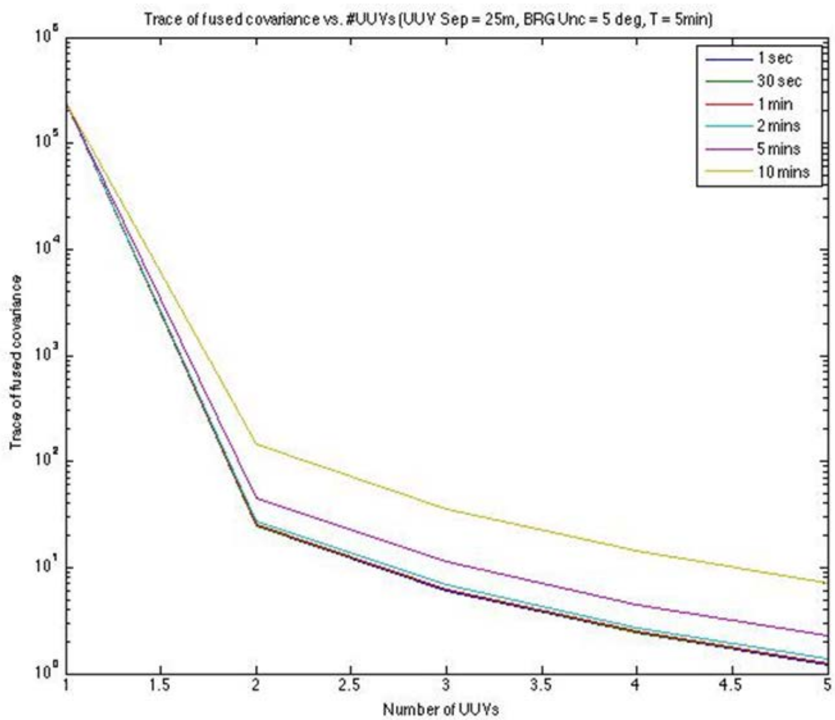

Figure E-6: Trace of fused covariance versus number of UUVs over time. The target velocity is ~10kts and the UUV velocity is ~6kts (in the +x-direction). UUV separation was 25m and bearing accuracy is +/-5 degrees.

These results confirm that the model is working correctly. The model is applied to an identical set of analyses as the static tracking problem of Section 3.1, but with a standardized velocity ratio of $\frac{V_{TGT}}{V_{UUV}} = 1.6$. This corresponds to a target velocity of 8kts and a UUV velocity of 5kts. Figure E-7 shows the results of varying UUV separation

distance for a standardized sensor accuracy of +/-5 degrees. Figure E-8 shows the results of varying sensor quality for a standardized UUV separation of 25m.

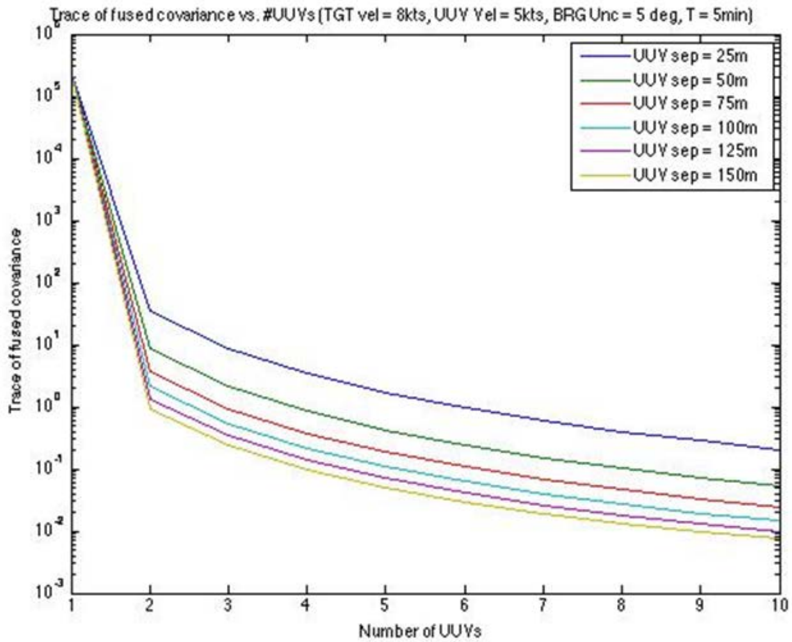

Figure E-7: Trace of fused covariance versus number of UUVs for various UUV separation distances at $V_{TGT} = 1.6V_{UUV}$. The time step is five minutes and bearing accuracy is +/-5 degrees.

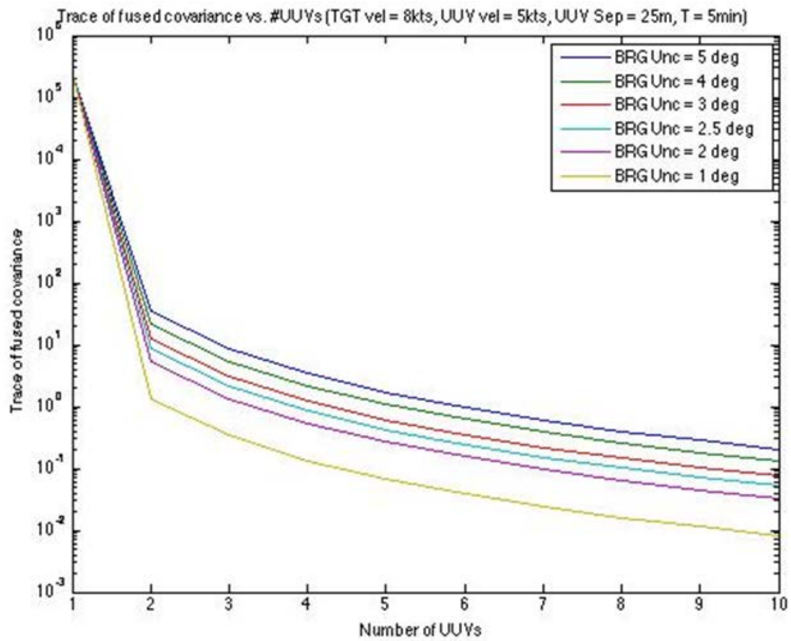

Figure E-8: Trace of fused covariance versus number of UUVs for various sensor accuracies at $V_{TGT} = 1.6V_{UUV}$. The time step is five minutes and the UUV separation distance is 25m.

These figures indicate that the UUV performance is similar to the static scenario in both analyses, though with slightly lower reduction in vehicle count for a given resolution. This is not a particularly useful result, so a third analysis varying a different parameter—speed ratio between the target and UUVs is attempted. The intent is to understand the relationship between resolution and the relative difference between target and vehicle speeds. Figure E-9 shows the results of this analysis for a standardized UUV separation of 25m and a bearing uncertainty of +/-5 degrees.

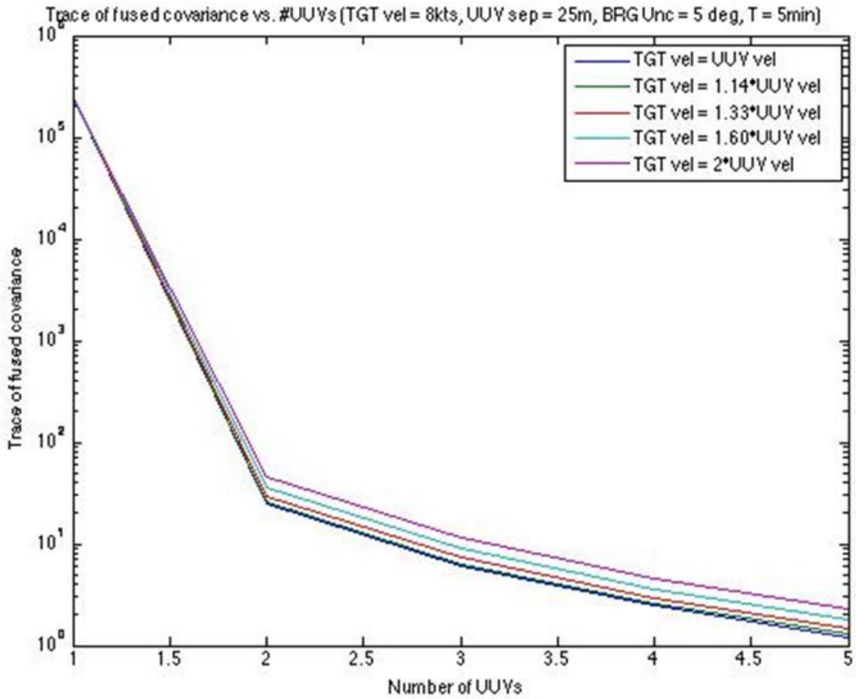

Figure E-9: Trace of fused covariance versus number of UUVs at different target/UUV speed ratios. The time step is five minutes; bearing uncertainty is +/-5 degrees; UUV separation distance is 25m.

At first glance, these results indicate the speed ratio does not significantly affect the resolution. Little is gained by matching UUV speed with target speed, or, conversely, little is lost by using a UUV speed of half the target speed. Perhaps this is an artifact of the performance parameters selected for the analysis (i.e. UUV separation distance and sensor quality), but an identical run with a UUV separation of 50m yields comparable results, though with greater resolution. Therefore, we confidently concluded target/UUV speed ratio is less of a concern for UUV tracking capability as sensor quality or vehicle separation distance. That said, this analysis does show target resolution can be achieved with greater energy efficiency by using more vehicles at a slower speed versus fewer vehicles at a higher speed. Since the required vehicle count for a given resolution does not dramatically reduce from one extreme of the speed ratio spectrum to the other (i.e., target speed equals UUV speed versus target speed equals twice UUV speed), this is a logical outcome that is easily verifiable by comparing energy consumption of a desired vehicle type for one case versus the other. The caveat to this particular conclusion is if the UUVs are tasked with tracking a target long term, the environmental conditions may

easily prevent maintaining contact on the target as UUV-target separation distance increases, in which case a higher UUV speed is more desirable.

D. MODEL CONCLUSIONS

A desired target resolution can be achieved by either improving the sensor quality, or varying UUV separation distance. The tradeoff is in the additional cost of improving the sensor quality, or in the potential degradation of the communication link between the vehicles due to increasing the separation between them.

The speed separation between the UUV and target has little impact on the number of vehicles required to attain a desired target resolution. Instead, the real effect in the speed separation is in the energy consumption required to achieve that resolution. More vehicles operating at slower speeds can achieve the same result as fewer vehicles operating at faster speeds, though with significantly less energy consumed. The tradeoff is in how much lateral separation the target achieves when a slower vehicle speed is used. A greater speed ratio (i.e., target speed/UUV speed) will result in greater distance separation, which would likely increase the probability of losing contact on the target due to signal attenuation.

Our model, therefore, gave useful insights to the design parameters affecting the employment of UUVs in a target-tracking mission. We expect the results of this model will better inform our analysis of alternatives for vehicle selection and employment in the broader mission area of intelligence, surveillance, and reconnaissance (ISR).

E. FUTURE WORK RECOMMENDATIONS

The coordinated sensing analysis does not consider the impact of different UUV configurations on target resolution. In other words, the effect of arranging the UUV pack in a configuration other than a straight line is not considered. Future work to identify optimal tracking configurations, such as a diamond or square pattern, would greatly enhance the operational employment of the vehicles. This may likely enhance energy efficiency, as well.

The relationship between target resolution and information transfer rate between vehicles is not strictly analyzed for in the model. Future work could investigate this

relationship and develop a cost-benefit analysis of using higher-data-rate undersea optical communications versus lower-data-rate acoustic communications between vehicles. A key to this future study is determining how much information really needs to be sent between vehicles, and how often the vehicles need to fuse the information to optimize target resolution. (Haertel 2013), (Cochenour 2012), and (Cox 2012) provide in-depth analysis of optical signal propagation in the undersea environment, as well as data rate limitations incurred from the undersea channel. Dr. Joe Rice of the Naval Postgraduate School Physics Department is an excellent resource for undersea acoustic communications.

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APPENDIX F: ANALYSIS OF ALTERNATIVES DATA

A. UUV ATTRIBUTE DATA

ISR Attributes Raw Data

Attribute/Alternative	(1) 21" Recoverable UUV	(1) 48" UUV	(1) 60" UUV	(4) 21" Expendable UUVs	(1) SSN	(4) 21" Recoverable UUVs
Mission effectiveness	0.5	0.5	0.5	0.83	1	0.97
Endurance	107.62	576.42	704.54	107.62	8640	107.62
Stealth	1.514	7.831	12.24	3.028	24.48	3.028
Ease of tactical employment	60	60	90	4	2	120
Mission flexibility	0.436	2.89	4.68	0.872	59.296	0.872
Years to field	1	1	2	2	0	2

ISR Value Function Scores (with SSN)

Attribute/Alternative	(1) 21" Recoverable UUV	(1) 48" UUV	(1) 60" UUV	(4) 21" Expendable UUVs	(1) SSN	(4) 21" Recoverable UUVs
Mission effectiveness	0.500	0.500	0.500	0.830	1.000	0.970
Endurance	0.012	0.067	0.082	0.012	1.000	0.012
Stealth	1.000	0.193	0.124	0.500	0.062	0.500
Ease of tactical employment	0.033	0.033	0.022	0.500	1.000	0.017
Mission flexibility	0.007	0.049	0.079	0.015	1.000	0.015
Years to field	0.889	0.889	0.667	0.667	1.000	0.667

ISR Value Function Scores (without SSN)

Attribute/Alternative	(1) 21" Recoverable UUV	(1) 48" UUV	(1) 60" UUV	(4) 21" Expendable UUVs	(4) 21" Recoverable UUVs
Mission effectiveness	0.500	0.500	0.500	0.830	0.970
Endurance	0.153	0.818	1.000	0.153	0.153
Stealth	1.000	0.193	0.124	0.500	0.500
Ease of tactical employment	0.033	0.033	0.022	0.500	0.017
Mission flexibility	0.093	0.618	1.000	0.186	0.186
Years to field	0.889	0.889	0.667	0.667	0.667

MCM Attributes Raw Data

Attribute/Alternative	(1) 21" Recoverable UUV	(1) 48" UUV	(1) 60" UUV	(6) 21" Recoverable UUVs	(1) SSN	(6) 21" Expendable UUVs
Mission effectiveness	22.6	22.6	22.6	78	9.8	78
Endurance	107.62	576.424	704.544	107.62	8640	107.62
Stealth	1.514	7.831	12.24	9.084	24.48	9.084
Ease of tactical employment	60	60	90	360	1440	12
Mission flexibility	0.436	2.89	4.68	1.744	59.296	4.36
Years to field	1	5	1	3	0	7

MCM Value Function Scores (with SSN)

Attribute/Alternative	(1) 21" Recoverable UUV	(1) 48" UUV	(1) 60" UUV	(6) 21" Recoverable UUVs	(1) SSN	(6) 21" Expendable UUVs
Mission effectiveness	0.226	0.226	0.226	0.780	0.098	0.780
Endurance	0.012	0.067	0.082	0.012	1.000	0.012
Stealth	1.000	0.193	0.124	0.167	0.062	0.167
Ease of tactical employment	0.033	0.033	0.022	0.006	0.001	1.000
Mission flexibility	0.007	0.049	0.079	0.029	1.000	0.074
Years to field	0.889	0.444	0.889	0.667	1.000	0.222

MCM Value Function Scores (without SSN)

Attribute/Alternative	(1) 21" Recoverable UUV	(1) 48" UUV	(1) 60" UUV	(6) 21" Recoverable UUVs	(6) 21" Expendable UUVs
Mission effectiveness	0.226	0.226	0.226	0.780	0.780
Endurance	0.153	0.818	1.000	0.153	0.153
Stealth	1.000	0.193	0.124	0.167	0.167
Ease of tactical employment	0.033	0.033	0.022	0.006	1.000
Mission flexibility	0.093	0.618	1.000	0.373	0.932
Years to field	1.000	0.500	1.000	0.750	0.250

IO Attributes Raw Data

Attribute/Alternative	(1) 21" Expendable UUV	(1) 48" UUV	(1) 60" UUV	(2) 21" Recoverable UUVs	(1) SSN	(2) 21" Expendable UUVs
Mission effectiveness	29	32	32	22	35	22
Endurance	107.62	576.424	704.544	107.62	8640	107.62
Stealth	1.514	7.831	12.24	3.028	24.48	3.028
Ease of tactical employment	2	60	90	60	2	4
Mission flexibility	0.436	2.89	4.68	0.872	59.296	4.36
Years to field	3	5	5	3	0	3

IO Value Function Scores (with SSN)

Attribute/Alternative	(1) 21" Expendable UUV	(1) 48" UUV	(1) 60" UUV	(2) 21" Recoverable UUVs	(1) SSN	(2) 21" Expendable UUVs
Mission effectiveness	0.759	0.688	0.688	1.000	0.629	1.000
Endurance	0.012	0.067	0.082	0.012	1.000	0.012
Stealth	1.000	0.193	0.124	0.500	0.062	0.500
Ease of tactical employment	1.000	0.033	0.022	0.016	1.000	0.500
Mission flexibility	0.007	0.049	0.079	0.015	1.000	0.015
Years to field	0.667	0.444	0.444	0.667	1.000	0.667

IO Value Function Scores (without SSN)

Attribute/Alternative	(1) 21" Expendable UUV	(1) 48" UUV	(1) 60" UUV	(2) 21" Recoverable UUVs	(2) 21" Expendable UUVs
Mission effectiveness	0.759	0.688	0.688	1.000	1.000
Endurance	0.153	0.818	1.000	0.153	0.153
Stealth	1.000	0.193	0.124	0.500	0.500
Ease of tactical employment	1.000	0.033	0.022	0.500	0.500
Mission flexibility	0.093	0.618	1.000	0.186	0.186
Years to field	0.667	0.444	0.444	0.667	0.667

Offensive Attack Attributes Raw Data

Attribute/Alternative	(1) 21" Expendable UUV	(1) 48" UUV	(1) 60" UUV	(4) 21" Expendable UUVs	(1) SSN	(15) Expendable Gliders
Mission effectiveness	0.063	0.25	0.235	0.26	2.73	0.45
Endurance	107.62	576.424	704.544	107.62	8640	430.48
Stealth	1.514	7.831	12.24	6.056	24.48	11.355
Ease of tactical employment	2	60	90	8	2	30
Mission flexibility	0.436	2.89	4.68	1.744	59.296	3.27
Years to field	6	7	7	6	0	7

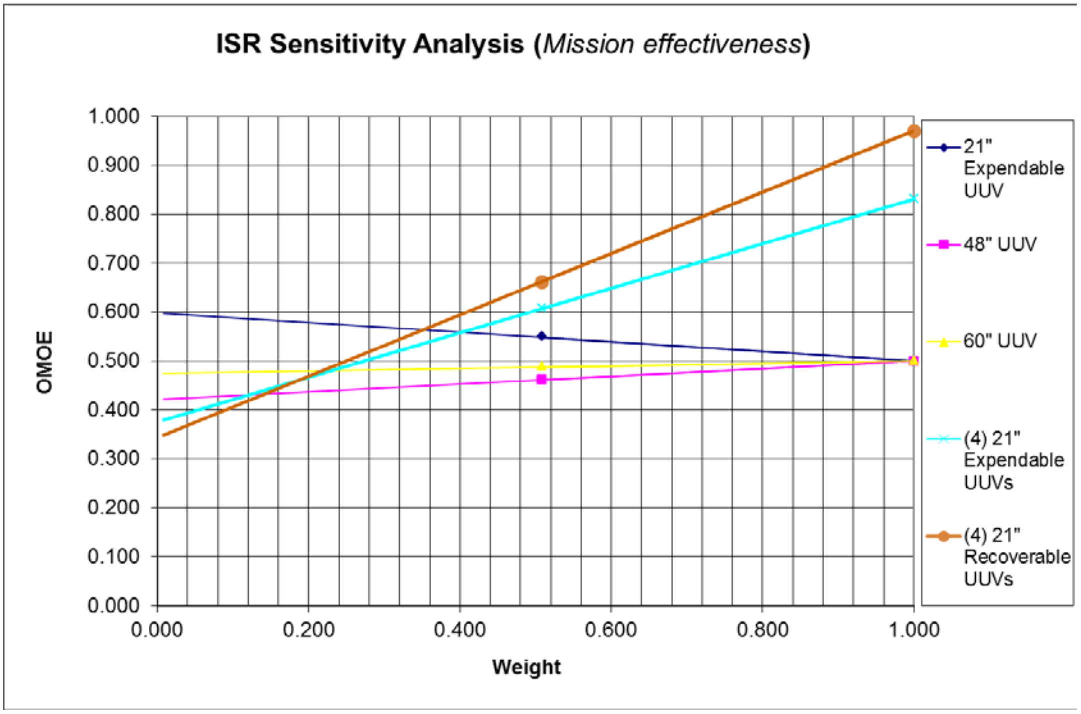
Offensive Attack Value Function Scores (with SSN)

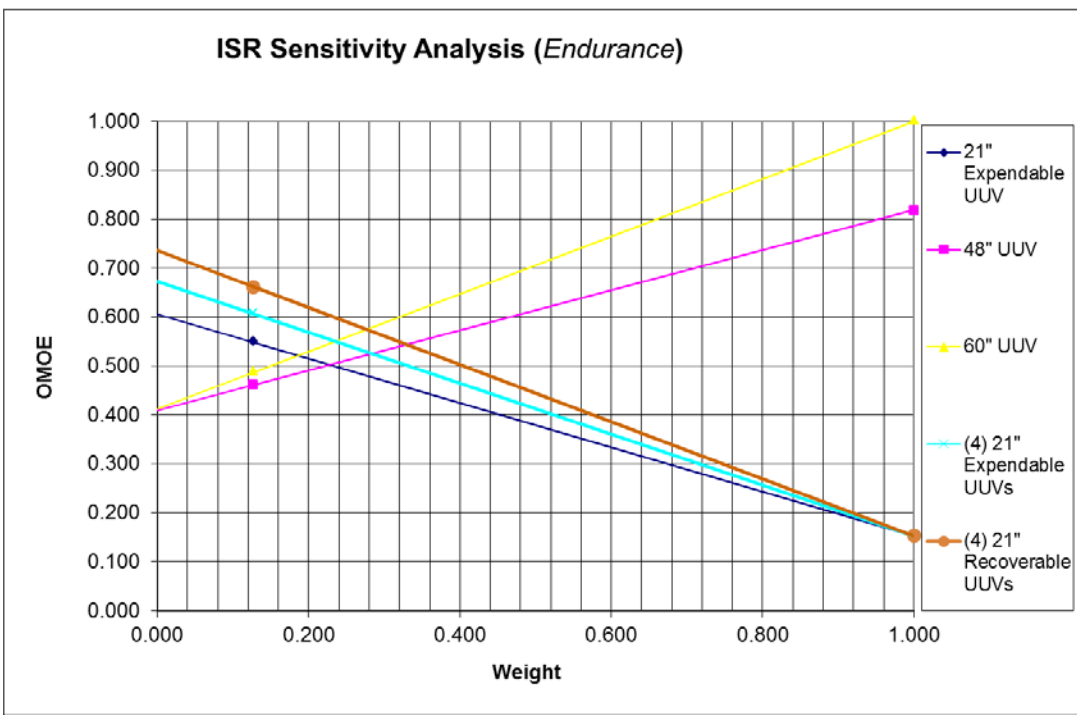
Attribute/Alternative	(1) 21" Expendable UUV	(1) 48" UUV	(1) 60" UUV	(4) 21" Expendable UUVs	(1) SSN	(15) Expendable Gliders
Mission effectiveness	0.023	0.092	0.086	0.095	1.000	0.165
Endurance	0.012	0.067	0.082	0.012	1.000	0.050
Stealth	1.000	0.193	0.124	0.250	0.062	0.133
Ease of tactical employment	1.000	0.033	0.022	0.250	1.000	0.067
Mission flexibility	0.007	0.049	0.079	0.029	1.000	0.055
Years to field	0.333	0.222	0.222	0.333	1.000	0.222

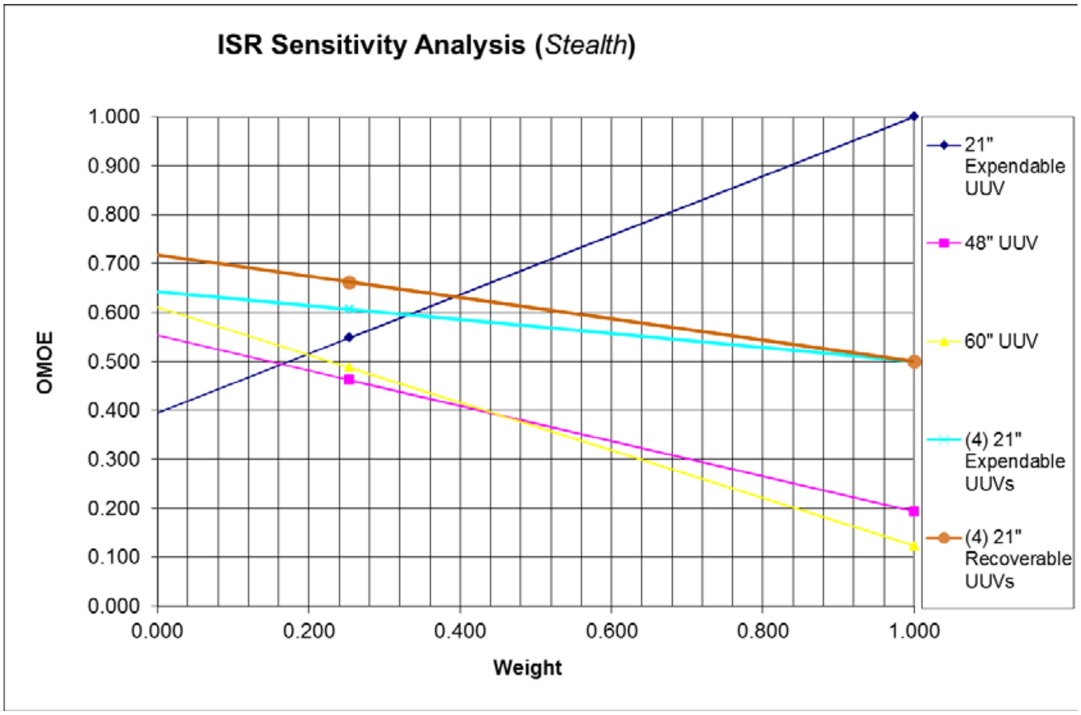
Offensive Attack Value Function Scores (without SSN)

Attribute/Alternative	(1) 21" Expendable UUV	(1) 48" UUV	(1) 60" UUV	(4) 21" Expendable UUVs	(15) Expendable Gliders
Mission effectiveness	0.140	0.556	0.522	0.578	1.000
Endurance	0.153	0.818	1.000	0.153	0.611
Stealth	1.000	0.193	0.124	0.250	0.133
Ease of tactical employment	1.000	0.033	0.022	0.250	0.067
Mission flexibility	0.093	0.618	1.000	0.373	0.699
Years to field	0.333	0.222	0.222	0.333	0.222

B. ANALYSIS OF ALTERNATIVES SENSIVITY PLOTS



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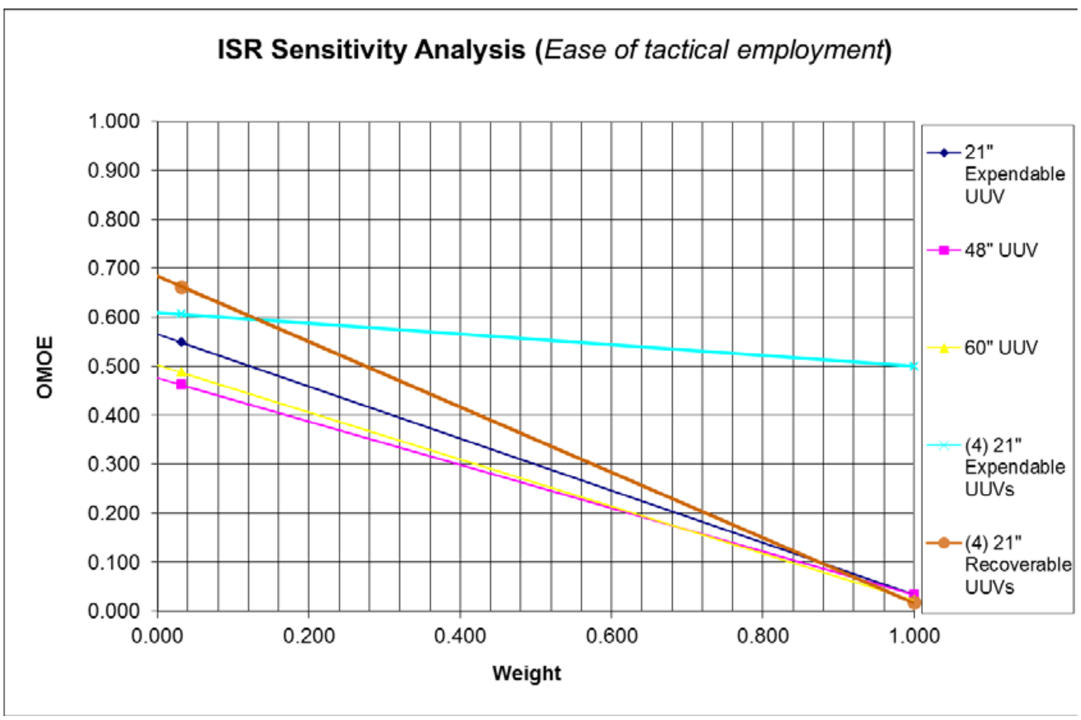
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0.000
0.200
0.400
0.600
0.800
1.000
21" Expendable UUV
48" UUV
60" UUV
(4) 21" Expendable UUVs
(4) 21" Recoverable UUVs


ISR Sensitivity Analysis (*Ease of tactical employment*)
OMOE
Weight
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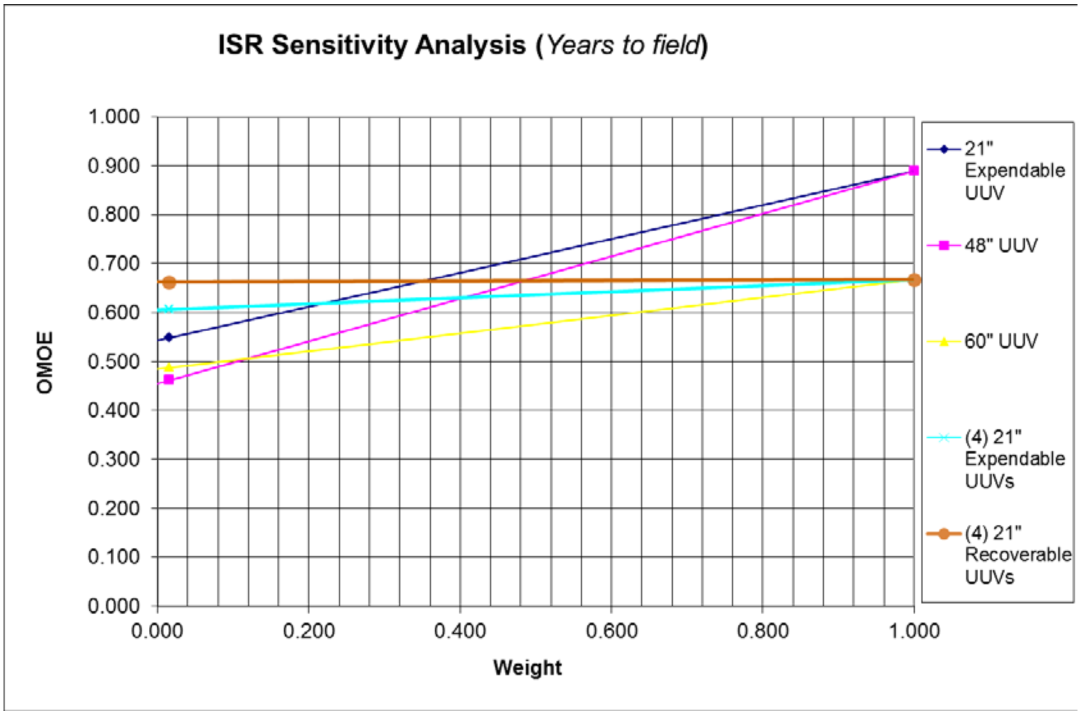
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0.000
0.200
0.400
0.600
0.800
1.000
21" Expendable UUV
48" UUV
60" UUV
(4) 21" Expendable UUVs
(4) 21" Recoverable UUVs


ISR Sensitivity Analysis (*Years to field*)
OMOE
Weight
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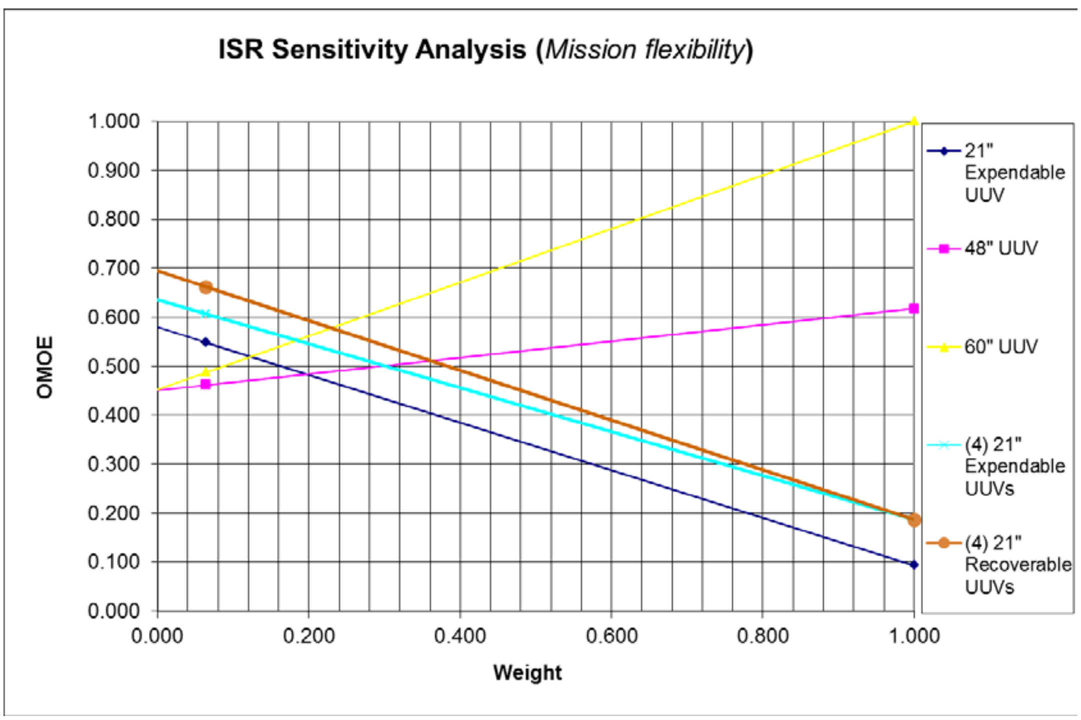
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0.000
0.200
0.400
0.600
0.800
1.000
21" Expendable UUV
48" UUV
60" UUV
(4) 21" Expendable UUVs
(4) 21" Recoverable UUVs


ISR Sensitivity Analysis (*Mission flexibility*)
OMOE
Weight
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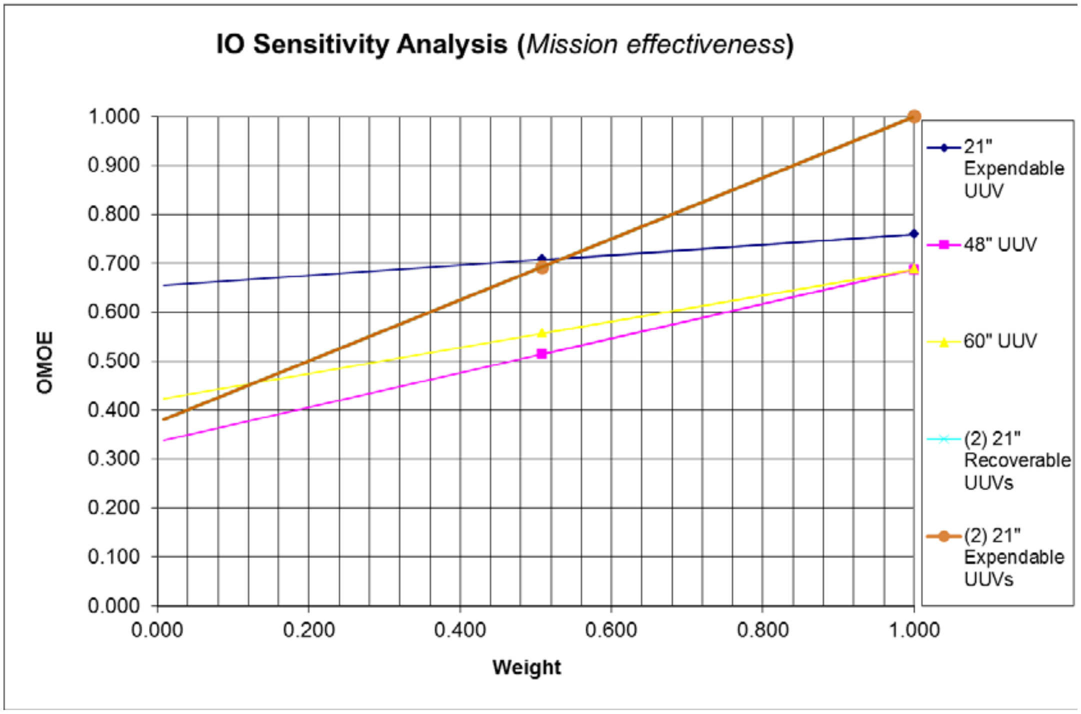
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0.000
0.200
0.400
0.600
0.800
1.000
21" Expendable UUV
48" UUV
60" UUV
(4) 21" Expendable UUVs
(4) 21" Recoverable UUVs


IO Sensitivity Analysis (*Mission effectiveness*)
OMOE
Weight
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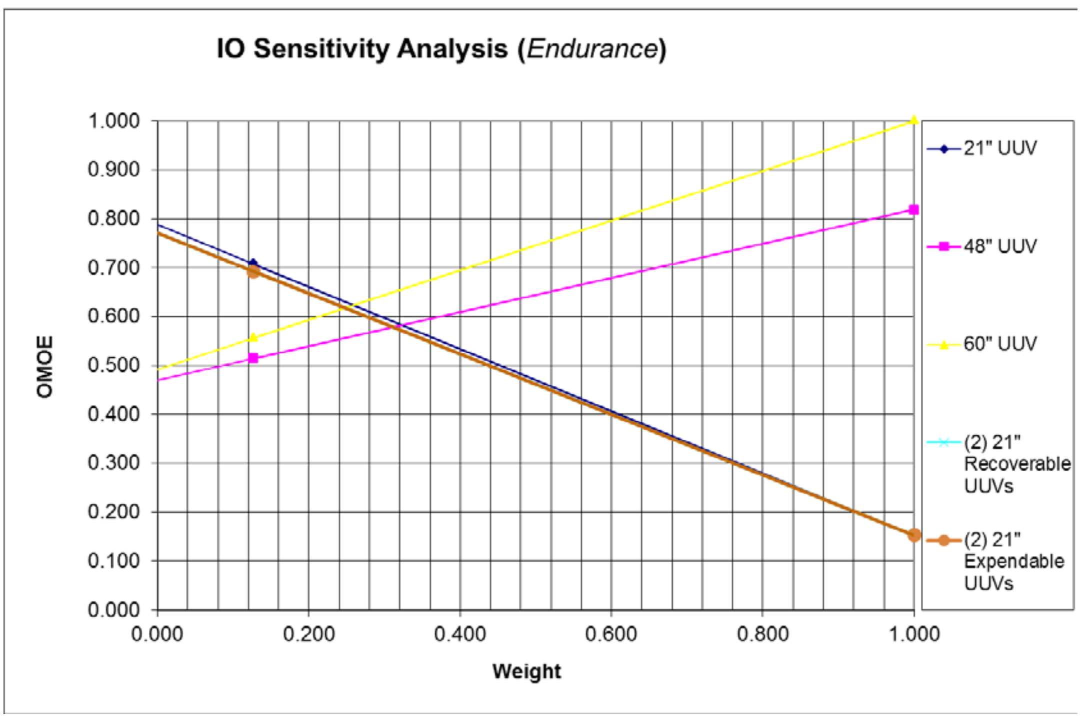
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0.000
0.200
0.400
0.600
0.800
1.000
21" Expendable UUV
48" UUV
60" UUV
(2) 21" Recoverable UUVs
(2) 21" Expendable UUVs


IO Sensitivity Analysis (*Endurance*)
OMOE
Weight
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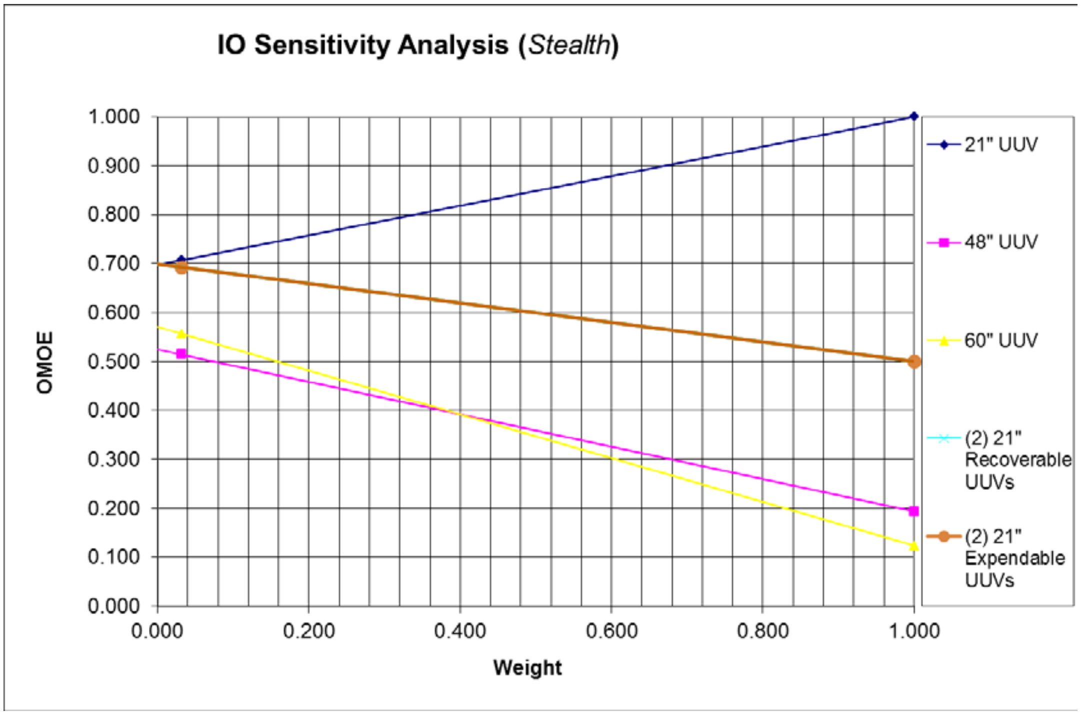
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0.000
0.200
0.400
0.600
0.800
1.000
21" UUV
48" UUV
60" UUV
(2) 21" Recoverable UUVs
(2) 21" Expendable UUVs


IO Sensitivity Analysis (*Stealth*)
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0.800
0.700
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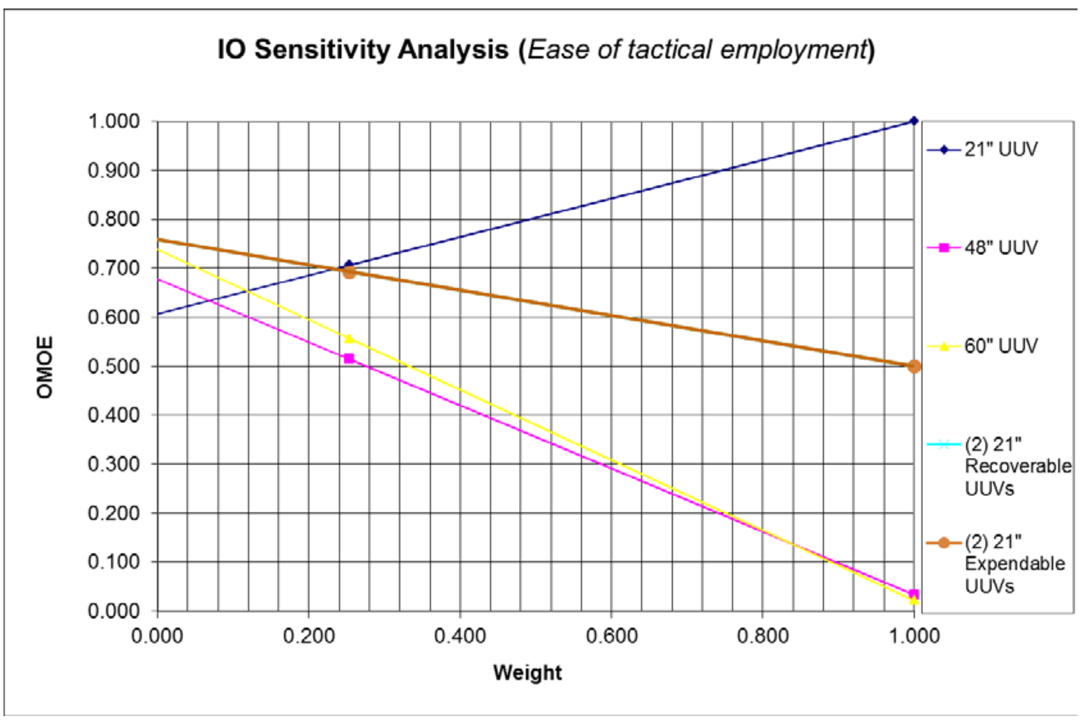
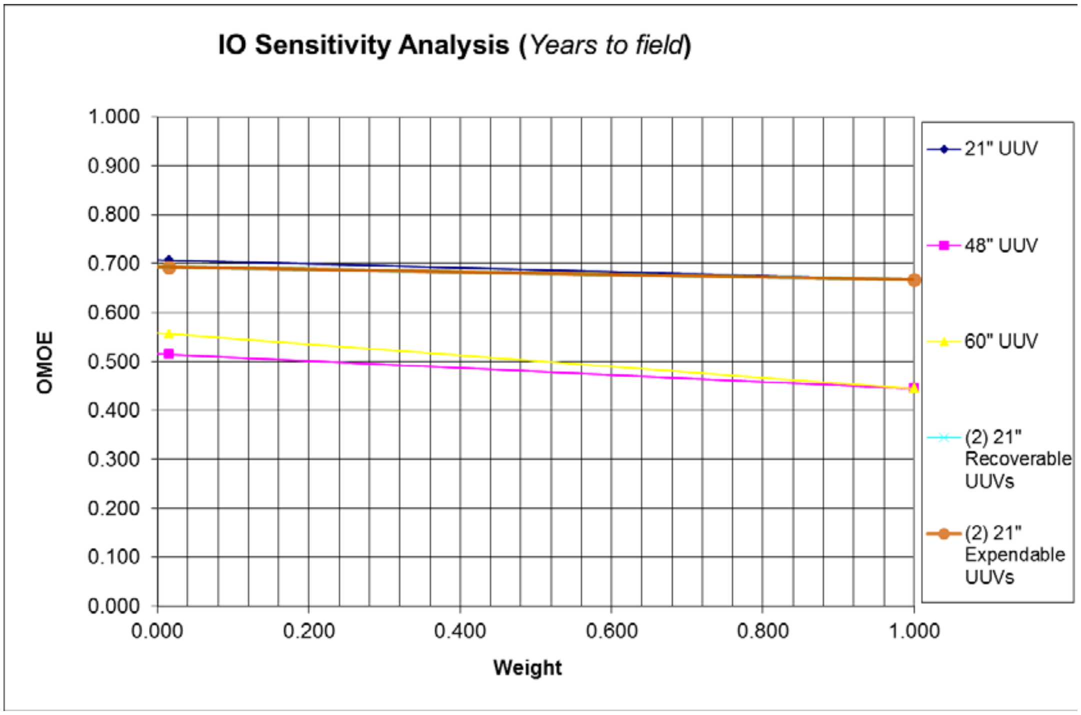
0.500
0.400
0.300
0.200
0.100
0.000
OMOE
0.000
0.200
0.400
0.600
0.800
1.000
Weight
21" UUV
48" UUV
60" UUV
(2) 21" Recoverable UUVs
(2) 21" Expendable UUVs


IO Sensitivity Analysis (*Ease of tactical employment*)
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
OMOE
0.000
0.200
0.400
0.600
0.800
1.000
Weight
21" UUV
48" UUV
60" UUV
(2) 21" Recoverable UUVs
(2) 21" Expendable UUVs


IO Sensitivity Analysis (*Years to field*)
OMOE
Weight
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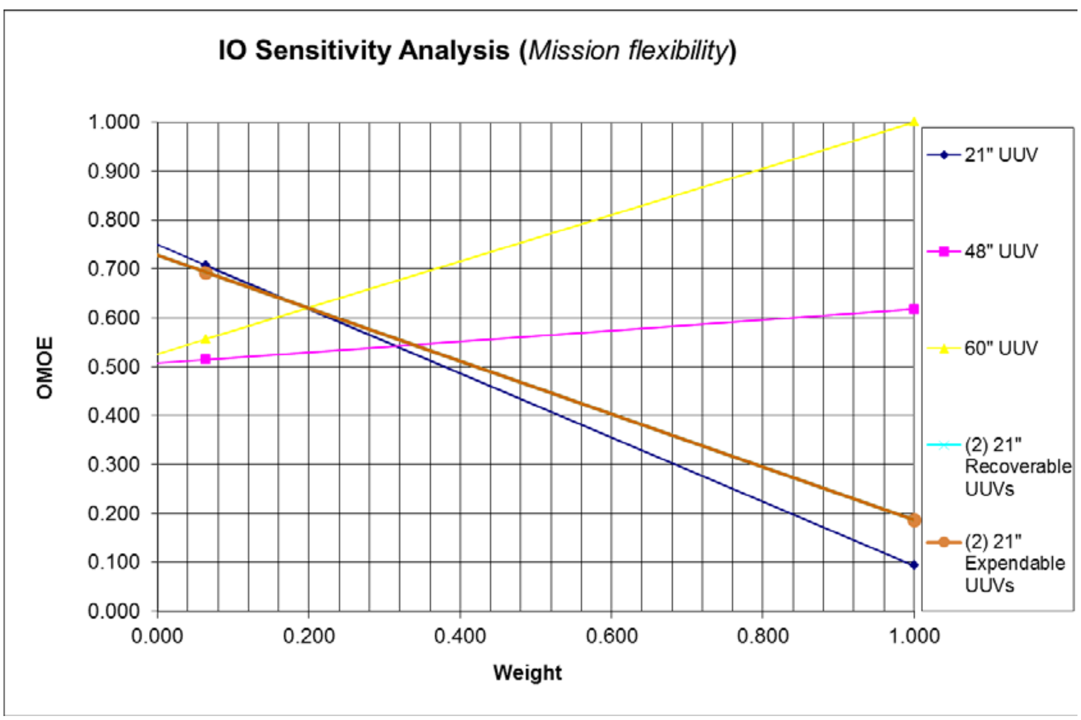
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0.000
0.200
0.400
0.600
0.800
1.000
21" UUV
48" UUV
60" UUV
(2) 21" Recoverable UUVs
(2) 21" Expendable UUVs


IO Sensitivity Analysis (*Mission flexibility*)
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Weight
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0.800
0.700
0.600
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0.400
0.300
0.200
0.100
0.000
0.000
0.200
0.400
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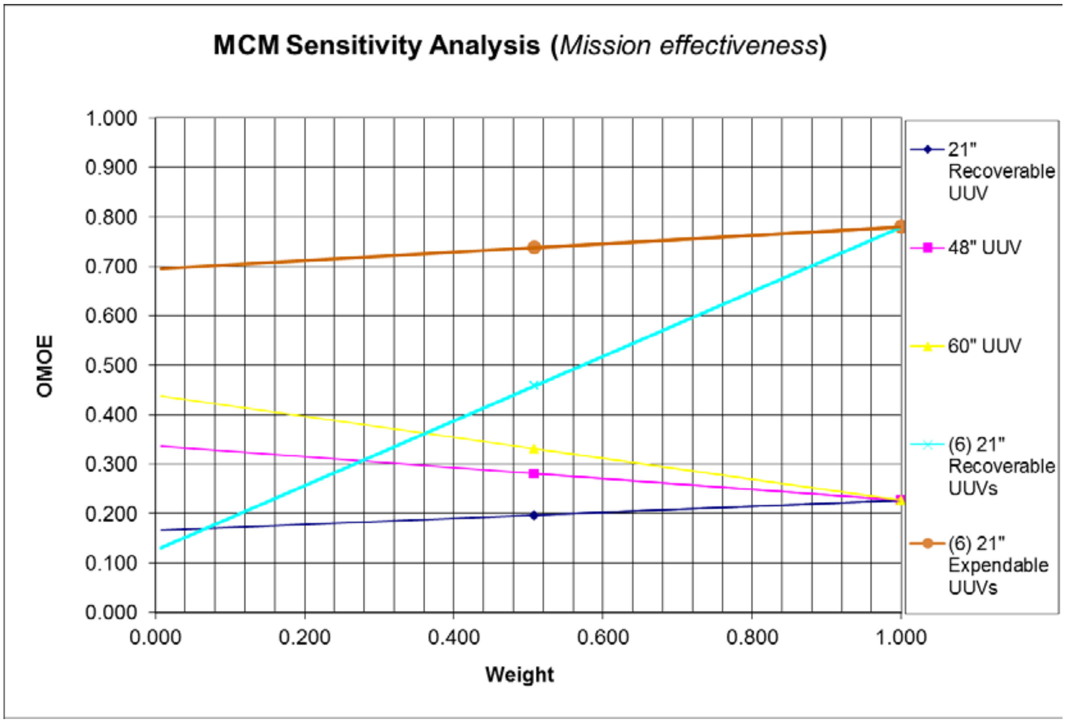
1.000
21" UUV
48" UUV
60" UUV
(2) 21" Recoverable UUVs
(2) 21" Expendable UUVs


MCM Sensitivity Analysis (*Mission effectiveness*)
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0.200
0.100
0.000
0.000
0.200
0.400
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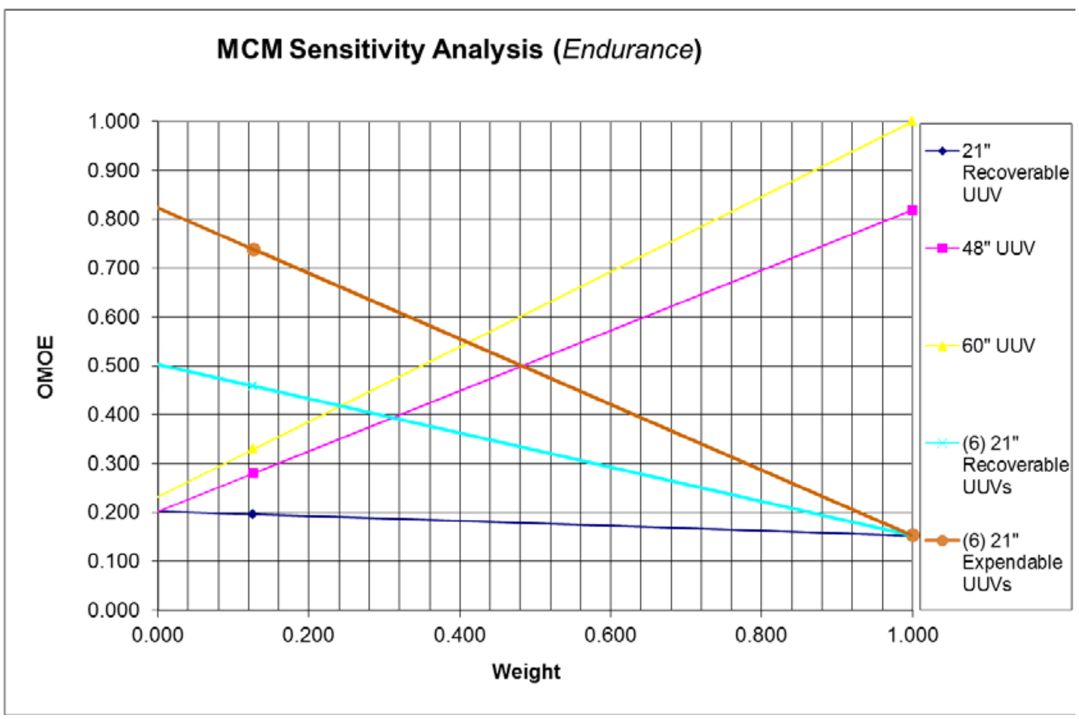
21" Recoverable UUV
48" UUV
60" UUV
(6) 21" Recoverable UUVs
(6) 21" Expendable UUVs


MCM Sensitivity Analysis (*Endurance*)
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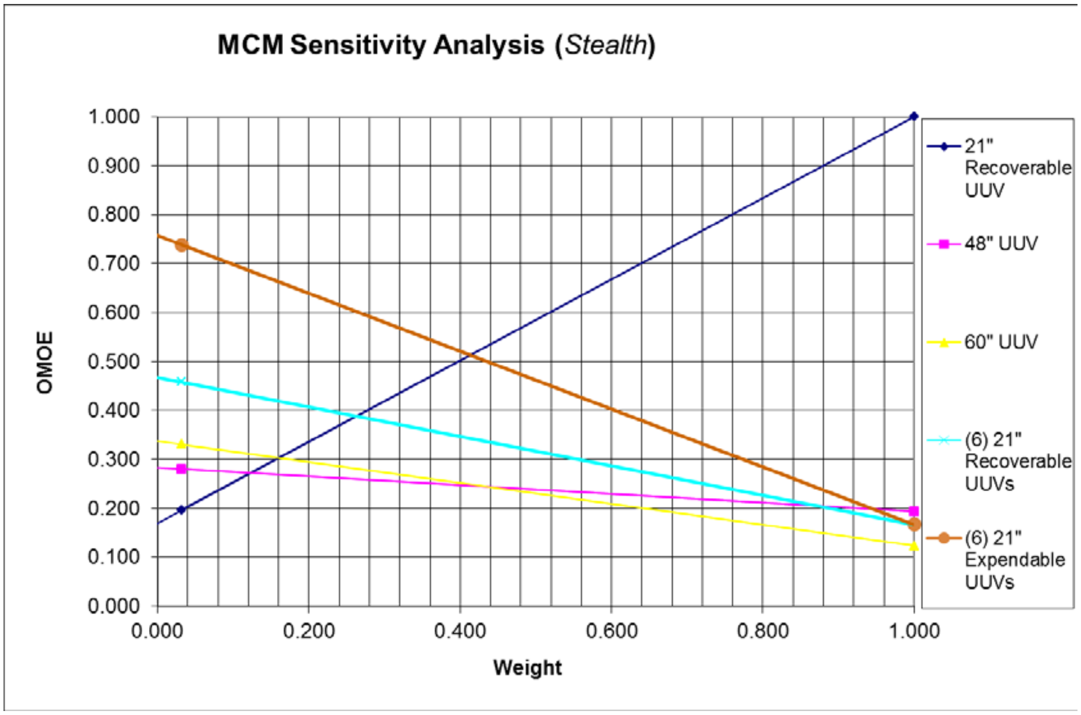
0.200
0.100
0.000
0.000
0.200
0.400
0.600
0.800
1.000
21" Recoverable UUV
48" UUV
60" UUV
(6) 21" Recoverable UUVs
(6) 21" Expendable UUVs


MCM Sensitivity Analysis (Stealth)
OMOE
Weight
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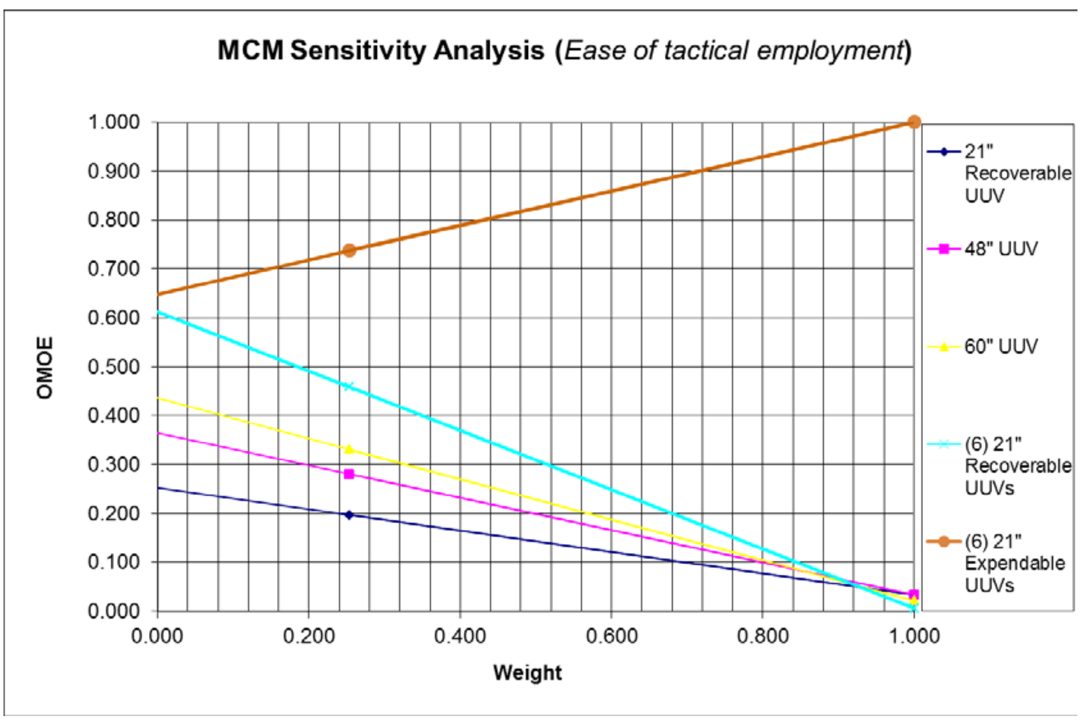
0.400
0.300
0.200
0.100
0.000
0.000
0.200
0.400
0.600
0.800
1.000
21" Recoverable UUV
48" UUV
60" UUV
(6) 21" Recoverable UUVs
(6) 21" Expendable UUVs


MCM Sensitivity Analysis (Ease of tactical employment)
OMOE
Weight
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0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0.000
0.200
0.400
0.600
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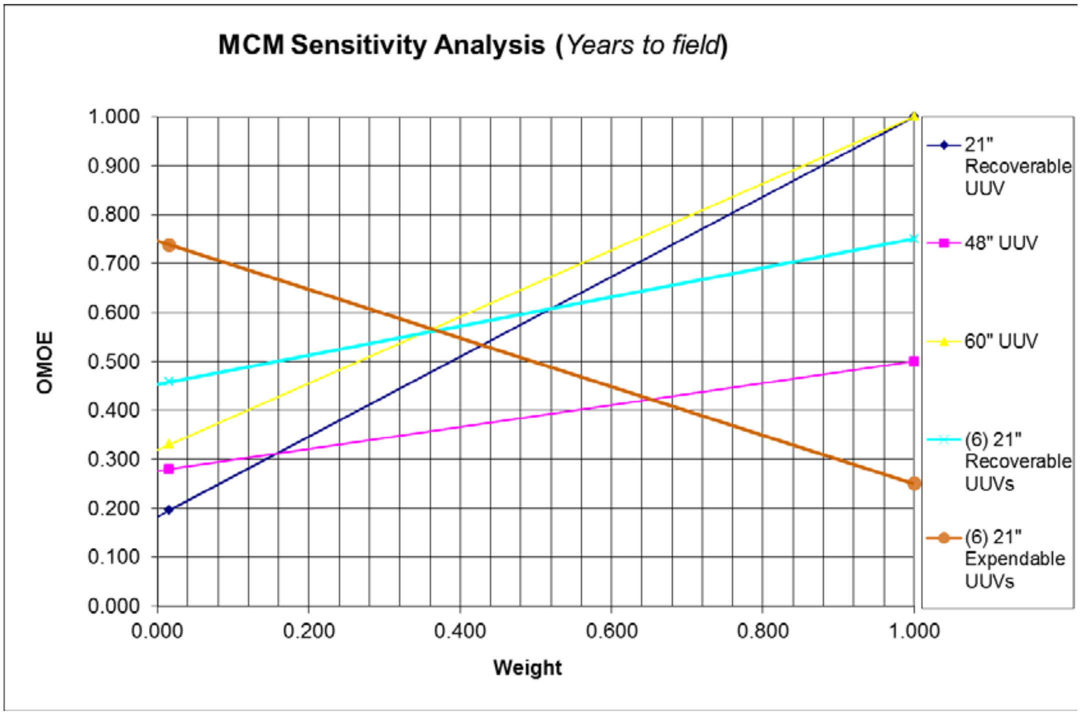
21" Recoverable UUV
48" UUV
60" UUV
(6) 21" Recoverable UUVs
(6) 21" Expendable UUVs


MCM Sensitivity Analysis (Years to field)
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0.800
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0.600
0.500
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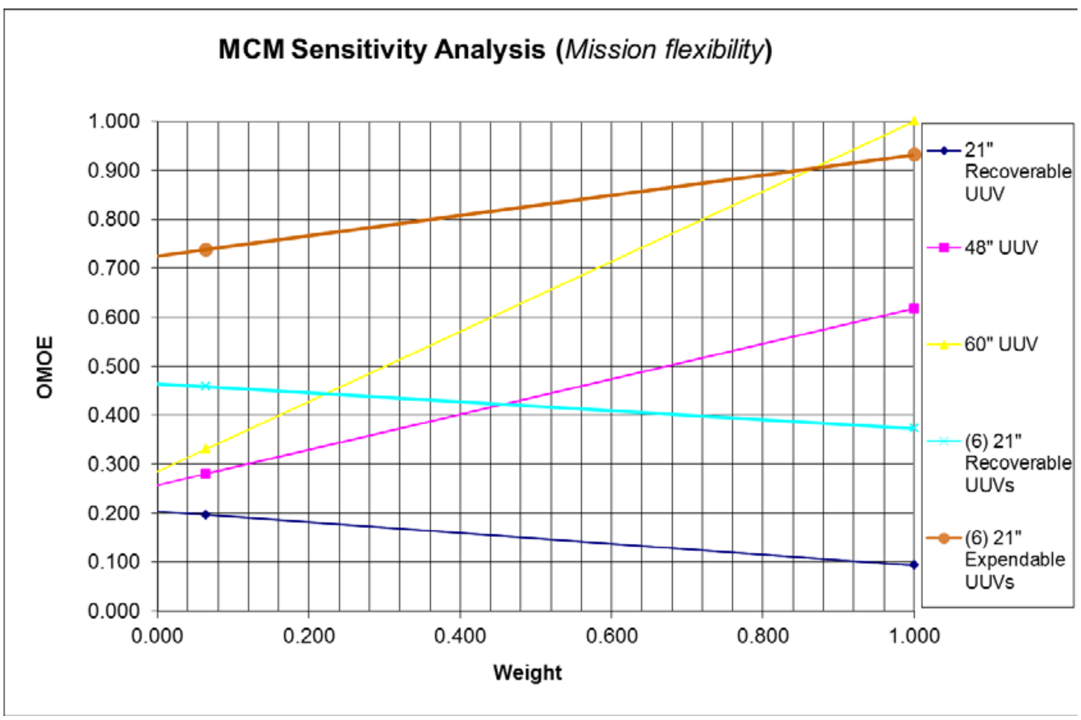
0.300
0.200
0.100
0.000
OMOE
0.000
0.200
0.400
0.600
0.800
1.000
Weight
21" Recoverable UUV
48" UUV
60" UUV
(6) 21" Recoverable UUVs
(6) 21" Expendable UUVs


MCM Sensitivity Analysis (Mission flexibility)
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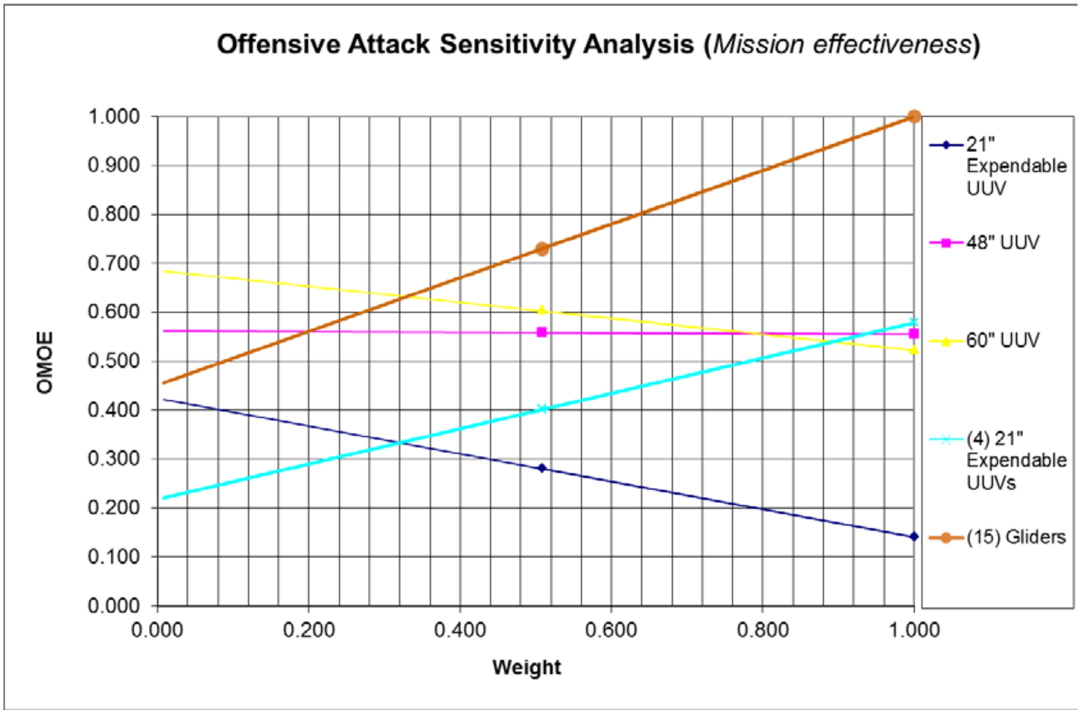
0.100
0.000
OMOE
0.000
0.200
0.400
0.600
0.800
1.000
Weight
21" Recoverable UUV
48" UUV
60" UUV
(6) 21" Recoverable UUVs
(6) 21" Expendable UUVs


Offensive Attack Sensitivity Analysis (*Mission effectiveness*)
OMOE
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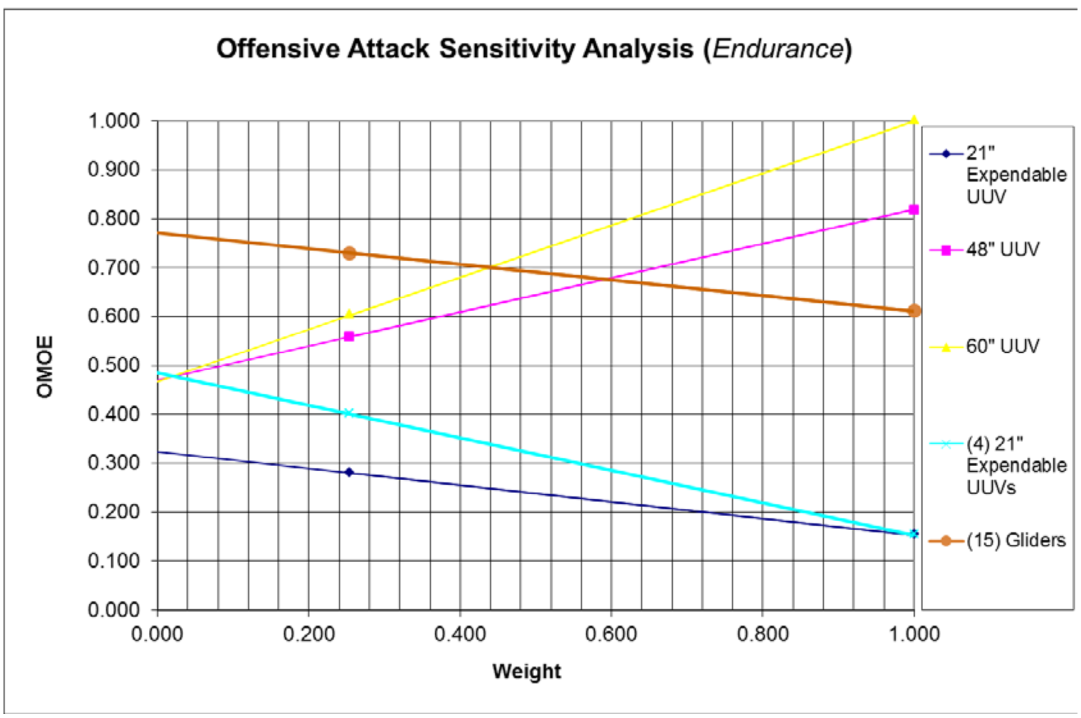
0.100
0.000
0.000
0.200
0.400
0.600
0.800
1.000
Weight
21" Expendable UUV
48" UUV
60" UUV
(4) 21" Expendable UUVs
(15) Gliders


Offensive Attack Sensitivity Analysis (*Endurance*)
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0.100
0.000
0.000
0.200
0.400
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0.800
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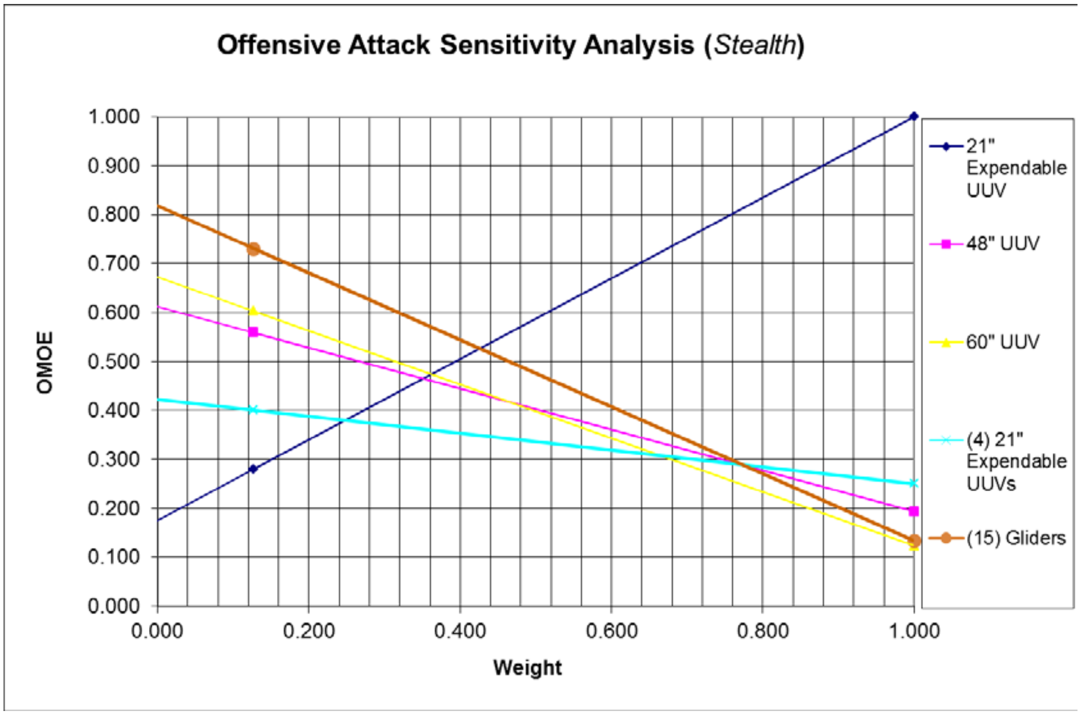
Weight
21" Expendable UUV
48" UUV
60" UUV
(4) 21" Expendable UUVs
(15) Gliders


Offensive Attack Sensitivity Analysis (*Stealth*)
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0.200
0.100
0.000
0.000
0.200
0.400
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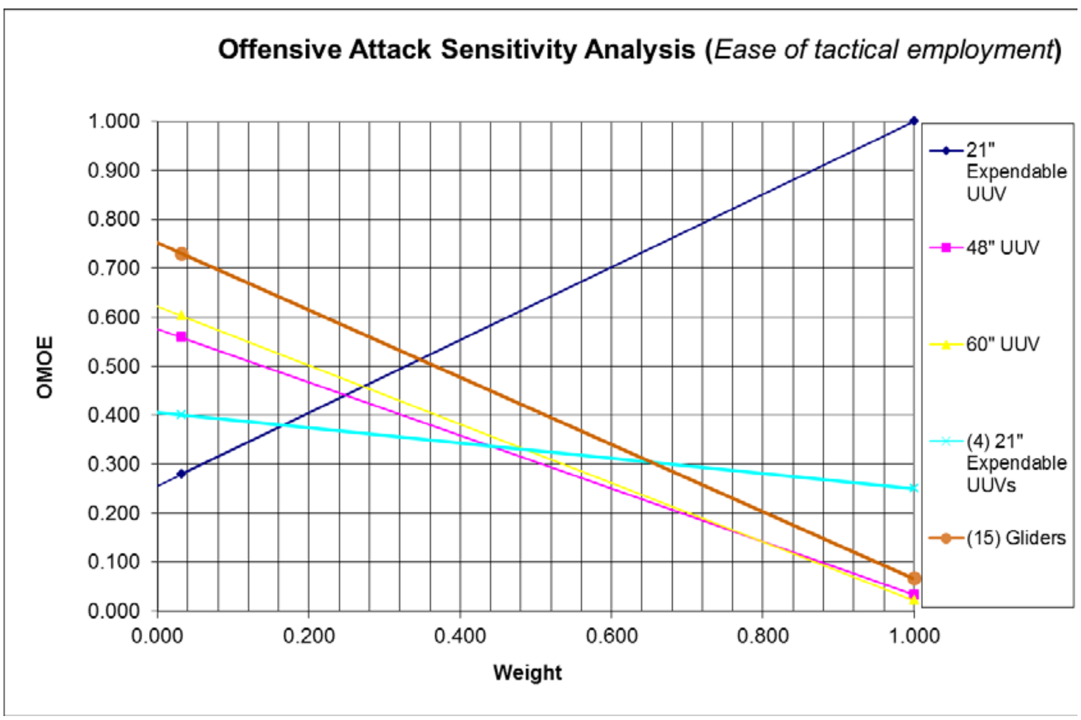
1.000
21" Expendable UUV
48" UUV
60" UUV
(4) 21" Expendable UUVs
(15) Gliders


Offensive Attack Sensitivity Analysis (*Ease of tactical employment*)
OMOE
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0.500
0.400
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0.200
0.100
0.000
0.000
0.200
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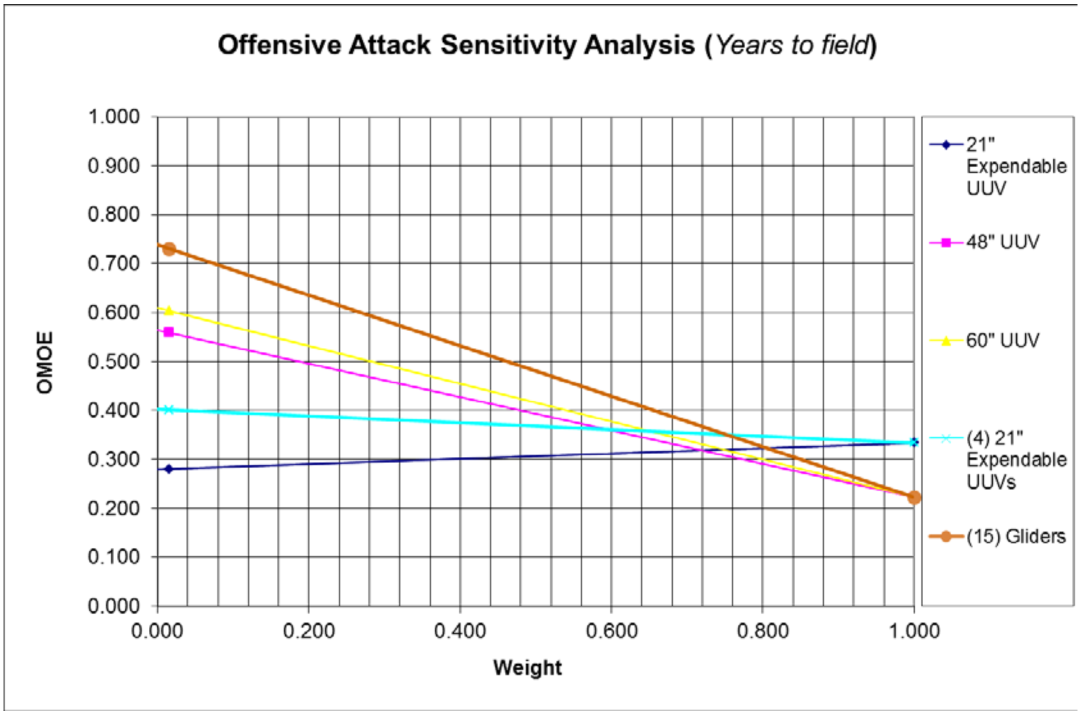
21" Expendable UUV
48" UUV
60" UUV
(4) 21" Expendable UUVs
(15) Gliders


Offensive Attack Sensitivity Analysis (*Years to field*)
OMOE
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0.800
0.700
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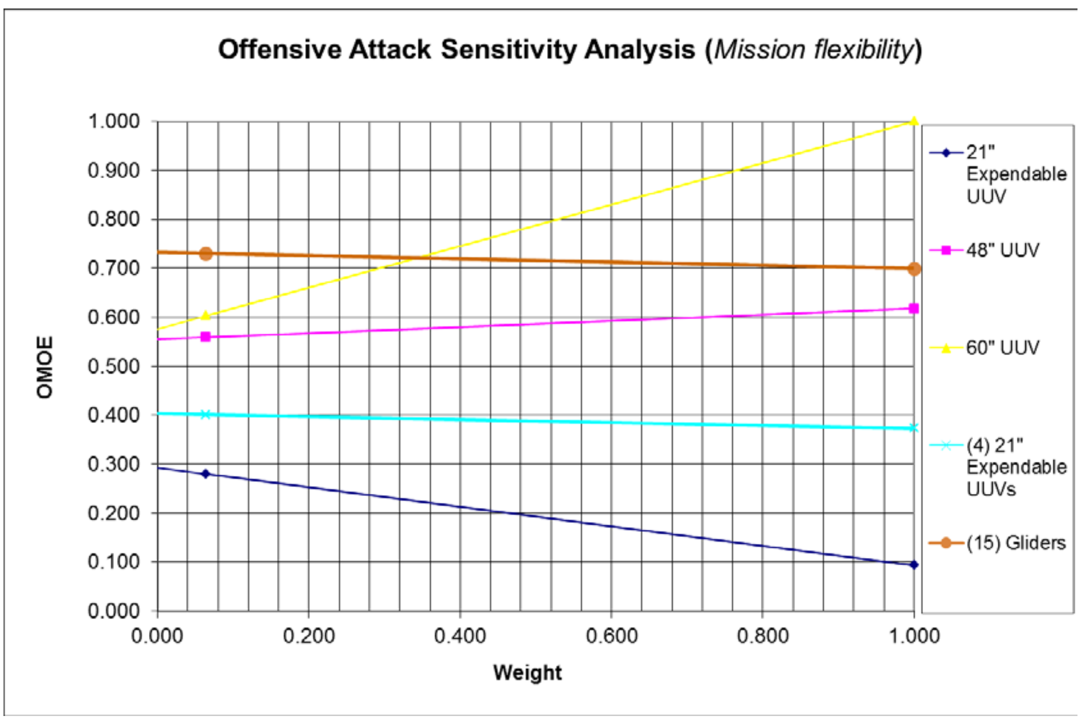
0.500
0.400
0.300
0.200
0.100
0.000
0.000
0.200
0.400
0.600
0.800
1.000
21" Expendable UUV
48" UUV
60" UUV
(4) 21" Expendable UUVs
(15) Gliders


Offensive Attack Sensitivity Analysis (*Mission flexibility*)
OMOE
Weight
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0.700
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0.500
0.400
0.300
0.200
0.100
0.000
0.000
0.200
0.400
0.600
0.800
1.000
21" Expendable UUV
48" UUV
60" UUV
(4) 21" Expendable UUVs
(15) Gliders

C. SUPPLEMENTAL POWER SOURCE ANALYSIS

A variety of power source solutions are considered with the exception of nuclear power solutions and those that have small probabilities of reaching sufficient TRL maturation over the next decade. Although there are many promising power alternatives for UUVs, there are not many that are at TRL-4 or above or that have been approved for use on submarines or surface ships. The two most practical alternatives within the study time frame are advanced lithium-ion batteries and a diesel engine/lithium-ion battery combination. Aside from the high TRLs of these alternatives, they do not involve the handling and storage of exotic or dangerous materials on shipboard environments. Current Navy ratings and specialties also have experience handling and operating both of these technologies. Installed shipboard casualty mitigation systems, such as fire protection, mitigate the risks associated with the storage of diesel fuel and battery systems. Another significant advantage for lithium-ion batteries is they are on track for submarine and surface combatant approval and use. Several approvals have already been granted for systems, such as the Bluefin Robotics Hovering Autonomous Underwater Vehicle (HAUV), which is designed for undersea hull and infrastructure inspection. As recently as April 2013, the standard 1.5 kWh Bluefin Robotics Subsea Battery was approved for use in the HAUV and for transport aboard naval aircraft (Bluefin Robotics 2013).

Figure F-1: Standard Bluefin Robotics 1.5 kWh Subsea Battery (From Bluefin Robotics 2013)

Multiple high profile incidents in commercial and military applications regarding lithium-ion batteries have both delayed their implementation and unrestricted use. These incidents provided a wealth of knowledge to industry regarding battery use and failure modes. The most recent publicized battery failure in commercial applications is the lithium-ion battery failure in the Boeing 787 Dreamliner. Thermal runaway of the batteries and a subsequent fire have been cited as the cause. This case unfolded during the SEA-19A study and provided a unique opportunity to examine the current state of lithium-ion battery technology and the main dangers associated with the technology; fire in the batteries and potential explosion. The Federal Aviation Administration grounding of the entire 787 Dreamliner fleet and subsequent recertification, exposed that technical problems with battery technologies may occur, but can be quickly overcome and are not technically insurmountable (Boeing 2013). This case also illustrates that further safety testing must occur before we place these onto operational units such as submarines where fire and explosion can be potential catastrophic.

The most significant failure of a lithium-ion in naval applications was the fire aboard the Advanced Seal Delivery Vehicle (ASDS) on November 9th, 2008. This failure, among other complications, effectively ended the ASDS program (Cavas 2008). The battery fire cascaded and caused extensive damage to the entire vehicle. Figure 2 shows the approximate arrangement of the battery that was destroyed in the fire. It is relatively

easy to see how the failure or overheating of a single cell could have a catastrophic cascading effect in the battery. This cascading failure proved especially difficult to stop due to the battery being located in an inaccessible space.

Following the failure, an extensive investigation by the USN and the battery manufacturer was conducted. During the January 11th, 2013 Menneken Series lecture at the Naval Postgraduate School a representative of Yardney stated that much has been learned regarding lithium-ion battery failure modes since the failure of the ASDS battery (Yardney 2013). The technology and design of the batteries has progressed to a degree that the risk of cascading failure is significantly reduced. Yardney's has demonstrated success in reliability and performance with lithium-ion batteries in several highly successful applications. Yardney lithium-ion batteries are utilized in critical applications such as the B-2 Spirit, and Mars Rovers.

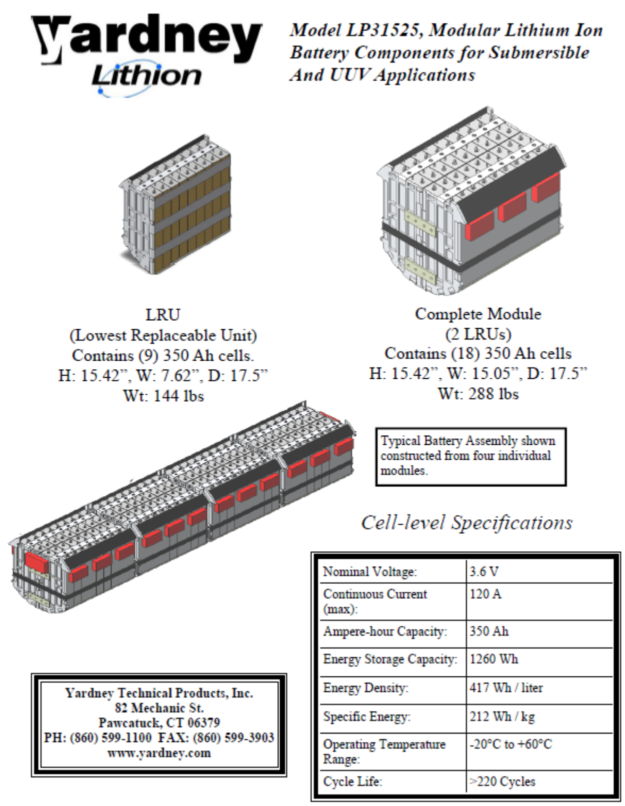
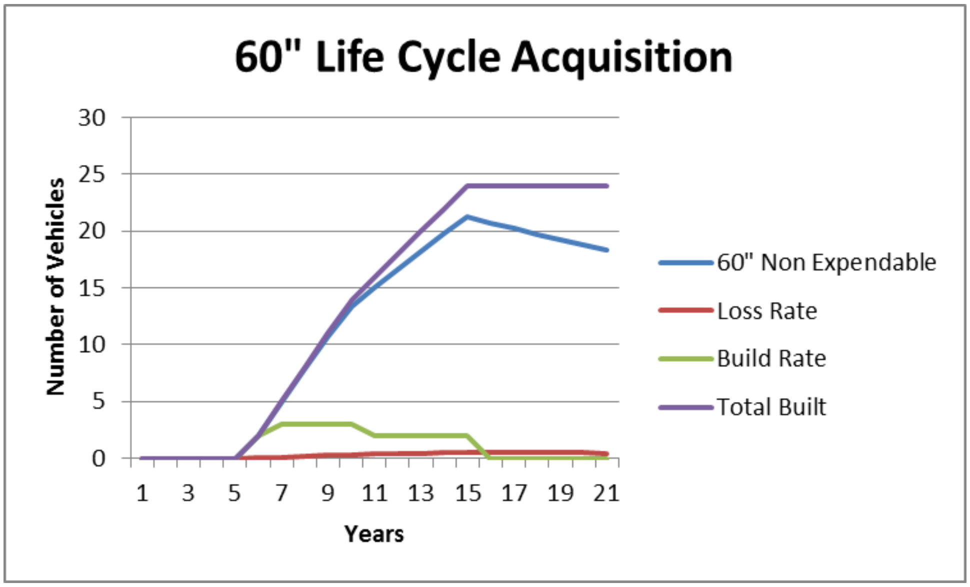
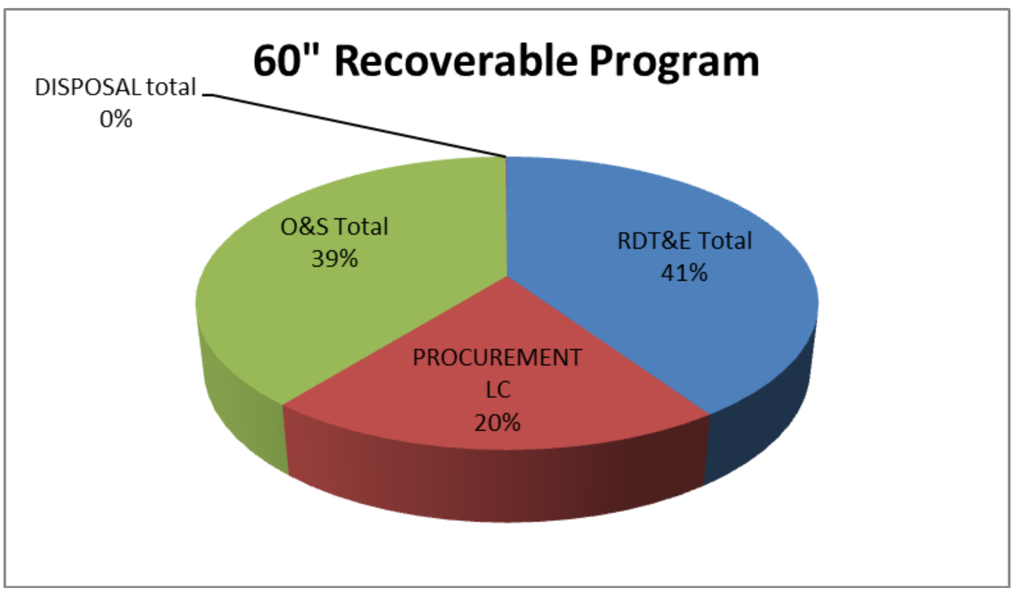


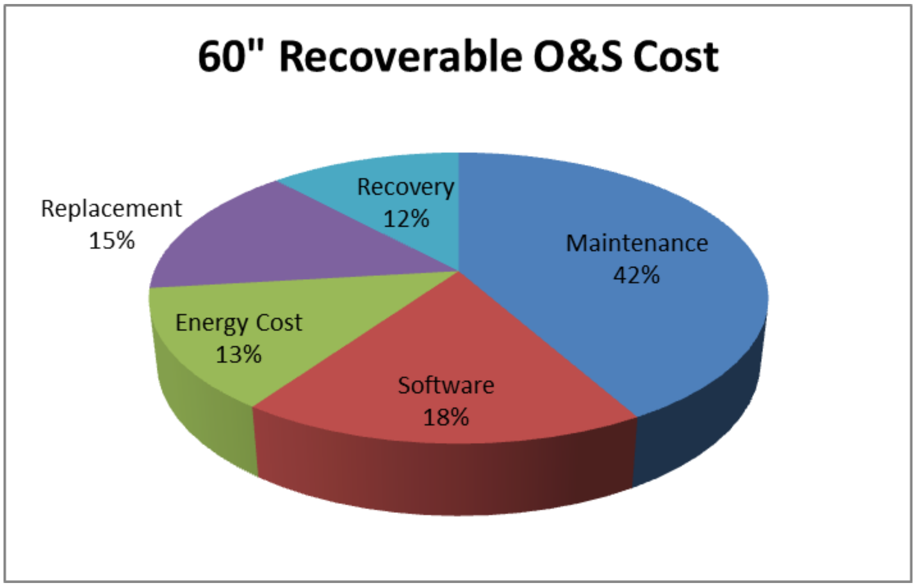
Figure F-2: Yardney ASDS Lithium Ion Battery Arrangement (From Yardney 2013)

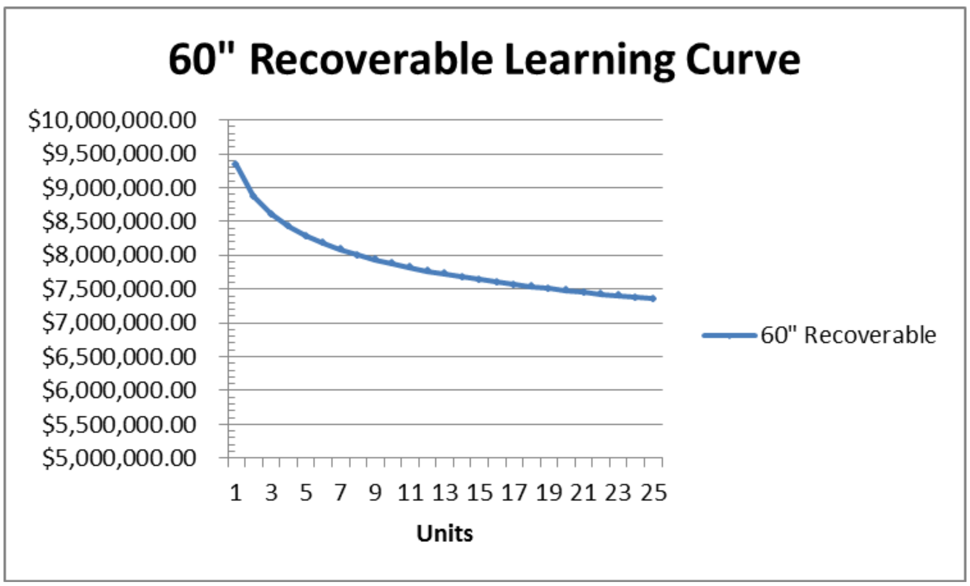
The ASDS vehicle and large format lithium-ion batteries pushed the battery technology envelope. The amount of risk undertaken with the early fielding of the systems on submarines may have been disproportionate with the utility of the vehicle. Uncontrollable battery fire on the ASDS or a similar vehicle while embarked on a submarine would certainly result in the loss of the vehicle and may even result in the loss of the submarine. The advancement of lithium-ion technology and successful fielding of lithium-ion batteries in automobiles and aircraft suggest that the technology may be ready for shipboard use, and even submarine use in the immediate future. An excellent pathway to utilize this technology would be extensive testing for shipboard use, followed by limited trials on surface ships, and then finally testing onboard submarines.

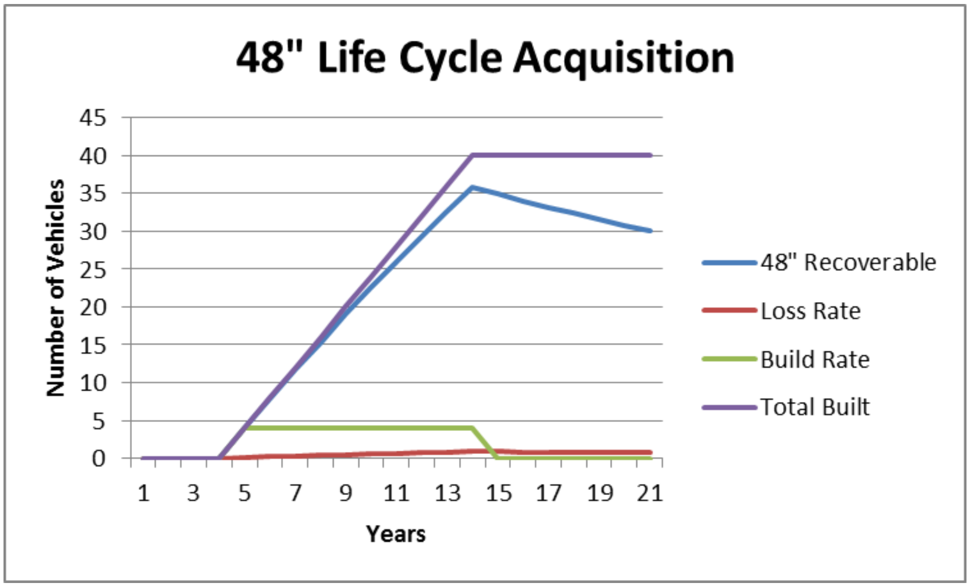
APPENDIX G: SUPPLEMENTAL COST ANALYSIS DATA

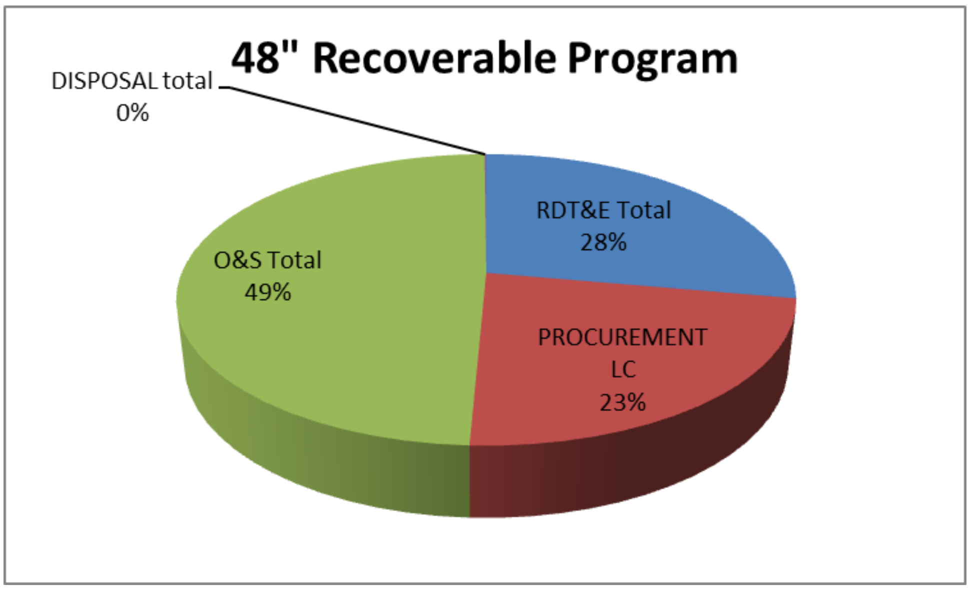


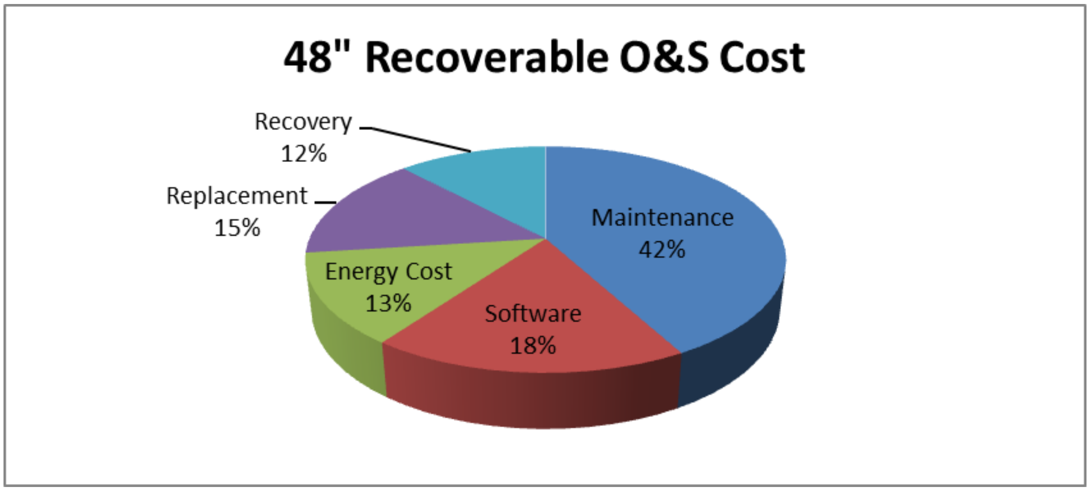


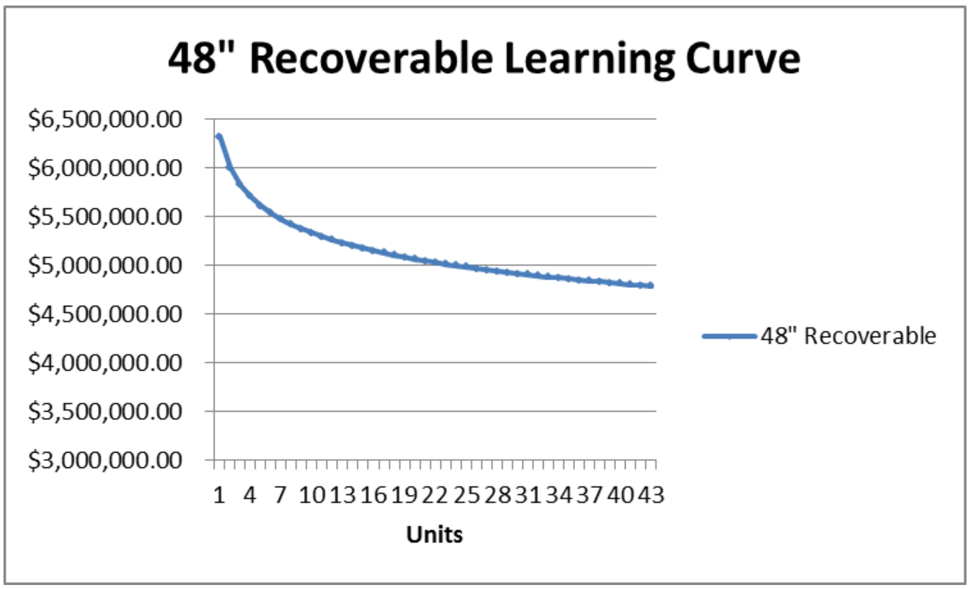

60" Recoverable O&S Cost
Recovery 12%
Replacement 15%
Maintenance 42%
Energy Cost 13%
Software 18%

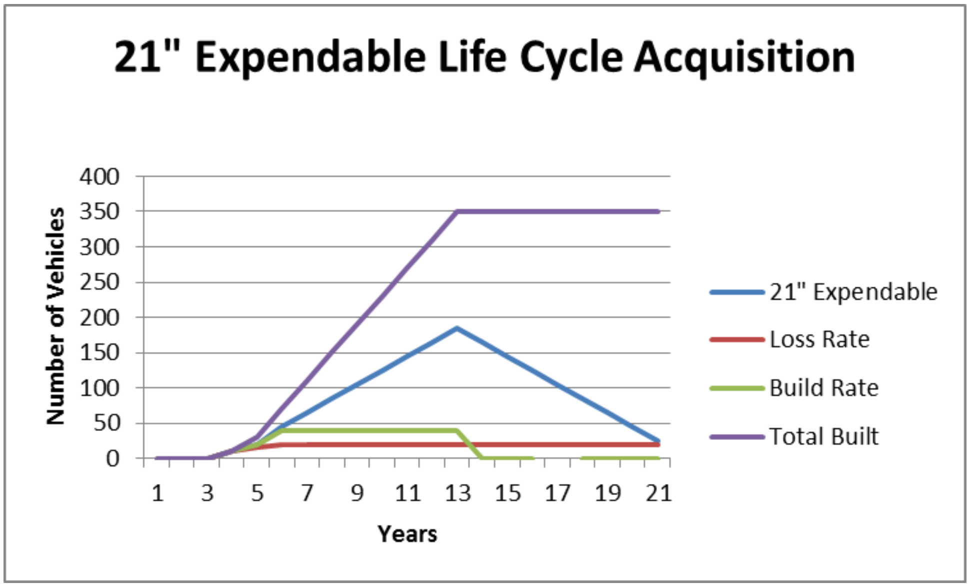

60" Recoverable Learning Curve
$10,000,000.00
$9,500,000.00
$9,000,000.00
$8,500,000.00
$8,000,000.00
$7,500,000.00
$7,000,000.00
$6,500,000.00
$6,000,000.00
$5,500,000.00
$5,000,000.00
1 3 5 7 9 11 13 15 17 19 21 23 25
Units
60" Recoverable

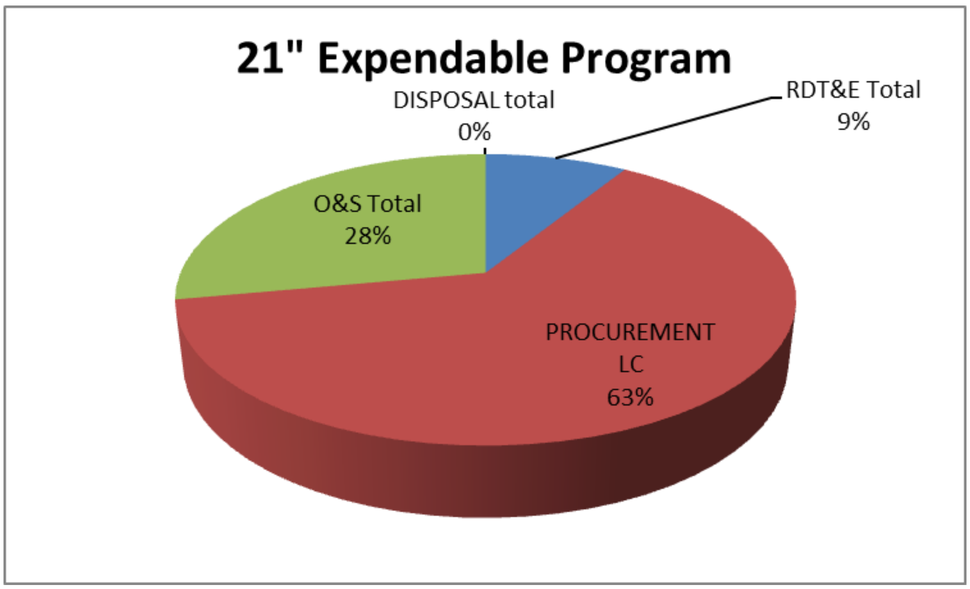

48" Life Cycle Acquisition
Number of Vehicles
45
40
35
30
25
20
15
10
5
0
1
3
5
7
9
11
13
15
17
19
21
Years
48" Recoverable
Loss Rate
Build Rate
Total Built

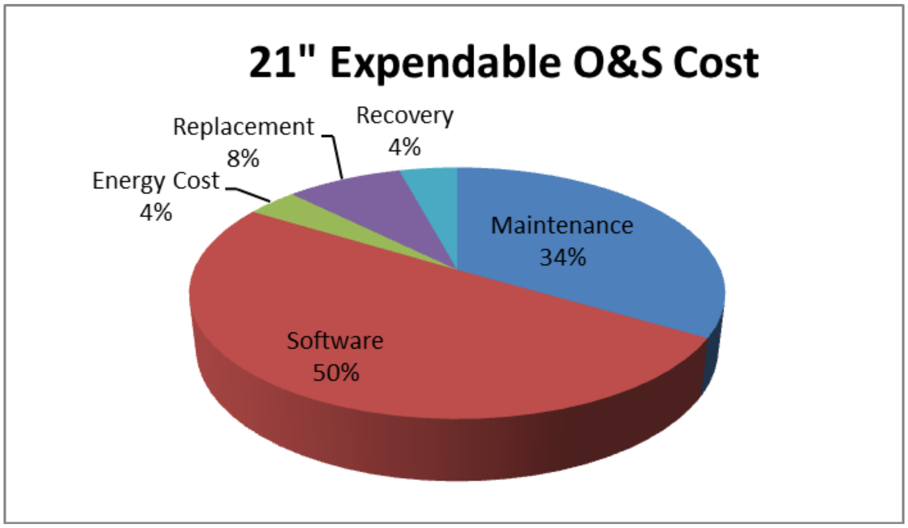

48" Recoverable Program
DISPOSAL total
0%
RDT&E Total
28%
O&S Total
49%
PROCUREMENT
LC
23%

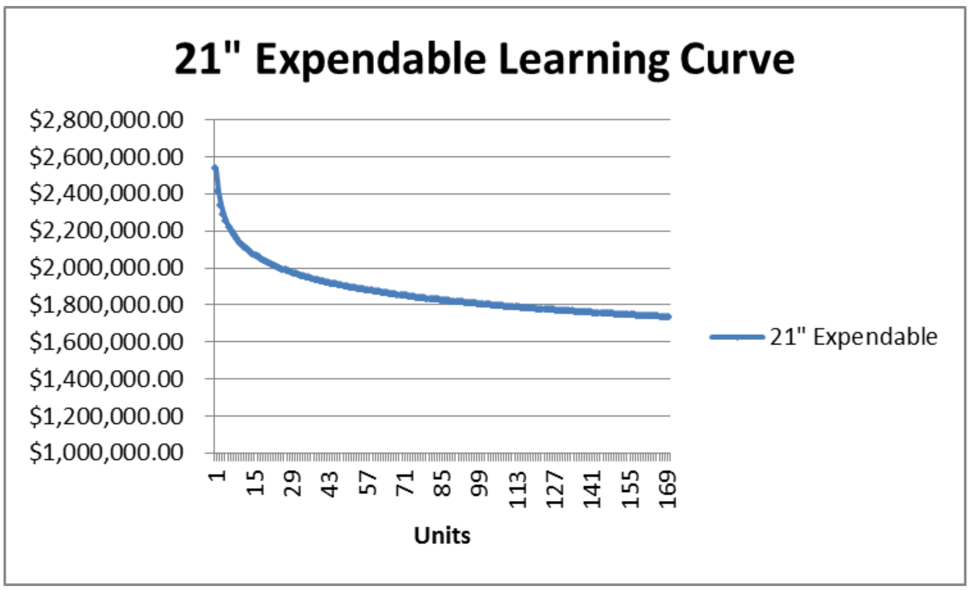

48" Recoverable O&S Cost
Recovery
12%
Replacement
15%
Maintenance
42%
Energy Cost
13%
Software
18%

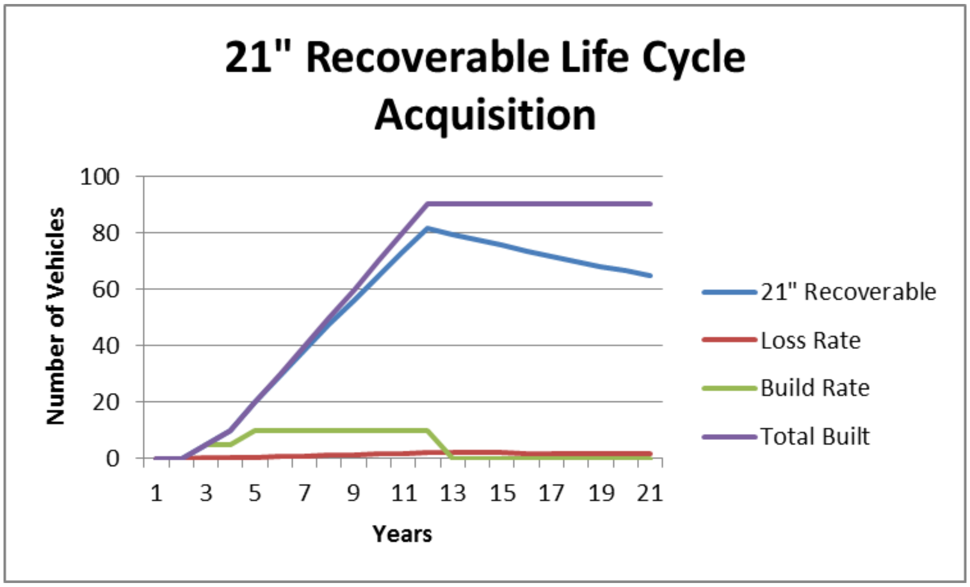

48" Recoverable Learning Curve
$6,500,000.00
$6,000,000.00
$5,500,000.00
$5,000,000.00
$4,500,000.00
$4,000,000.00
$3,500,000.00
$3,000,000.00
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43
Units
48" Recoverable

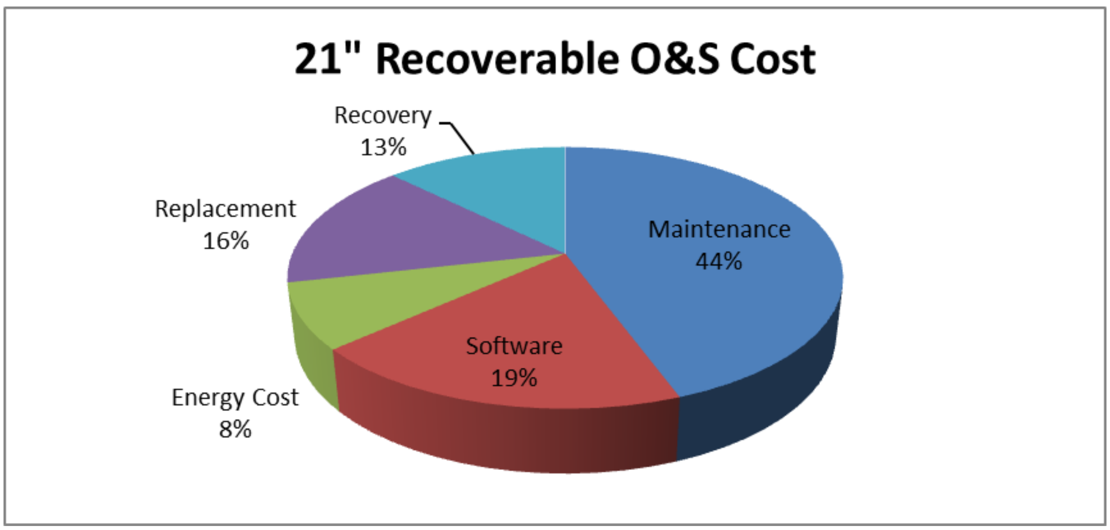

21" Expendable Life Cycle Acquisition
400
350
300
250
200
150
100
50
0
Number of Vehicles
1
3
5
7
9
11
13
15
17
19
21
Years
21" Expendable
Loss Rate
Build Rate
Total Built

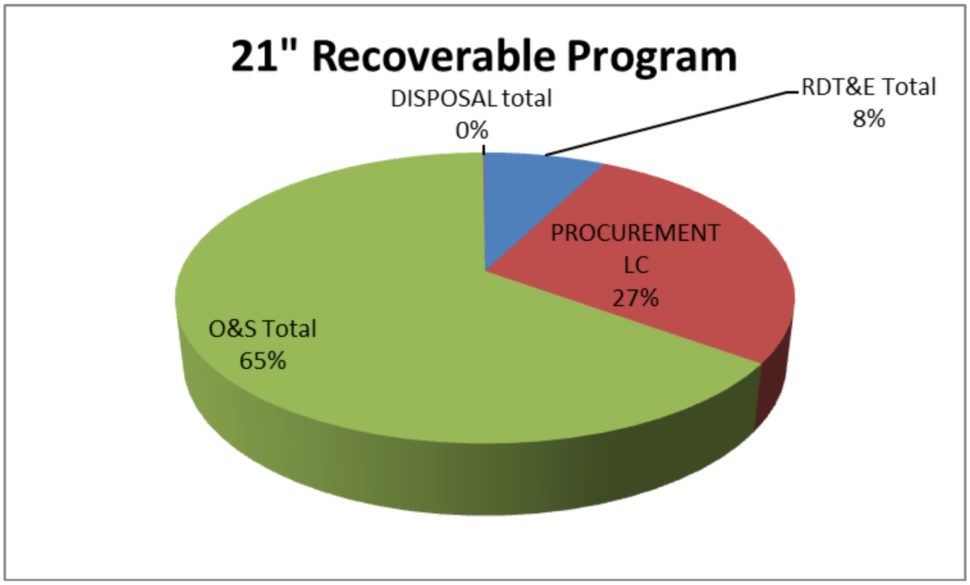

21" Expendable Program
DISPOSAL total
0%
RDT&E Total
9%
O&S Total
28%
PROCUREMENT
LC
63%

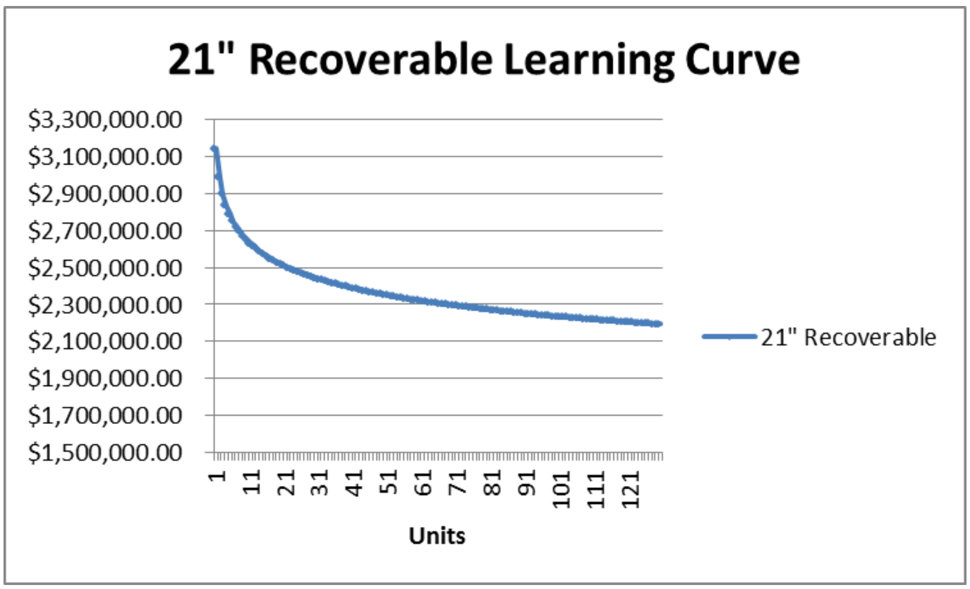

21" Expendable O&S Cost
Replacement 8%
Recovery 4%
Energy Cost 4%
Maintenance 34%
Software 50%

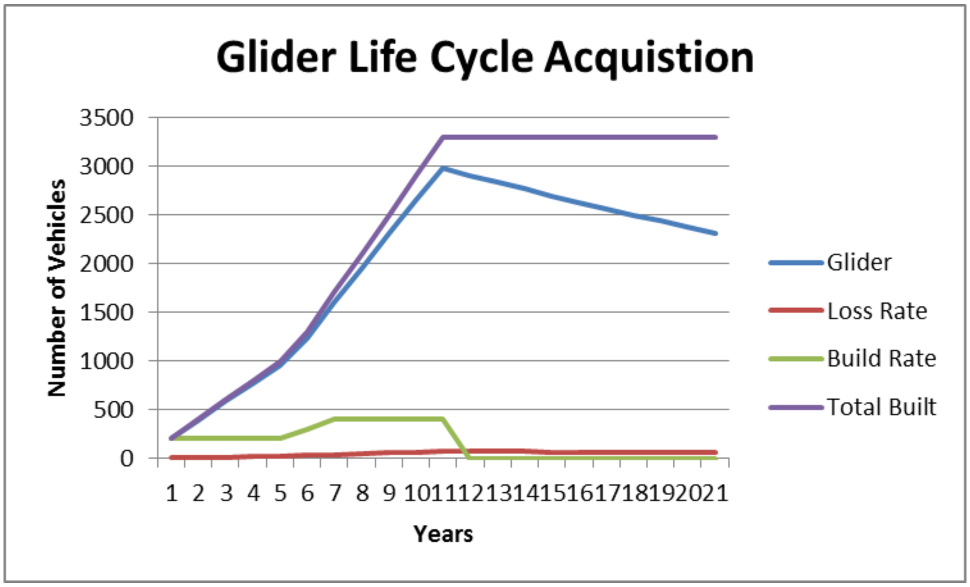

21" Expendable Learning Curve
$2,800,000.00
$2,600,000.00
$2,400,000.00
$2,200,000.00
$2,000,000.00
$1,800,000.00
$1,600,000.00
$1,400,000.00
$1,200,000.00
$1,000,000.00
1
15
29
43
57
71
85
99
113
127
141
155
169
Units
21" Expendable


21" Recoverable Life Cycle Acquisition
Number of Vehicles
100
80
60
40
20
0
1
3
5
7
9
11
13
15
17
19
21
Years
21" Recoverable
Loss Rate
Build Rate
Total Built

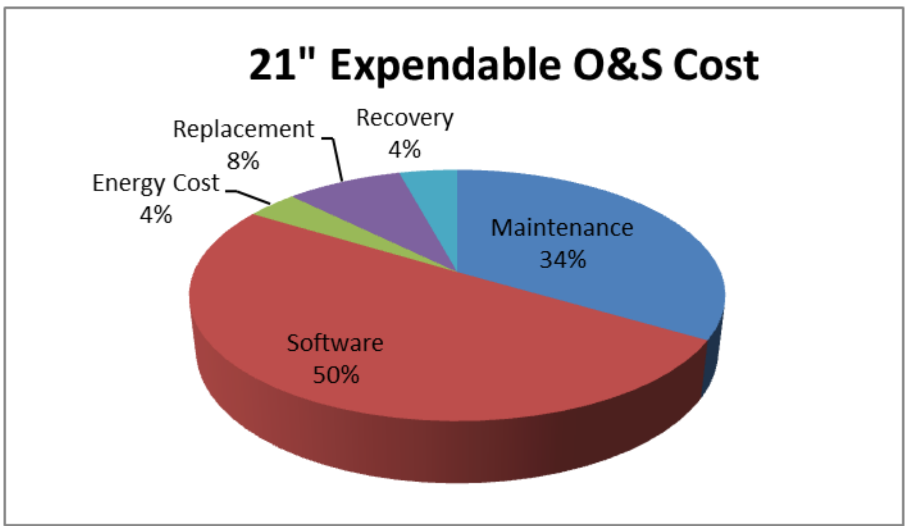

21" Recoverable O&S Cost
Recovery 13%
Replacement 16%
Maintenance 44%
Software 19%
Energy Cost 8%


21" Recoverable Program
DISPOSAL total
0%
RDT&E Total
8%
PROCUREMENT
LC
27%
O&S Total
65%

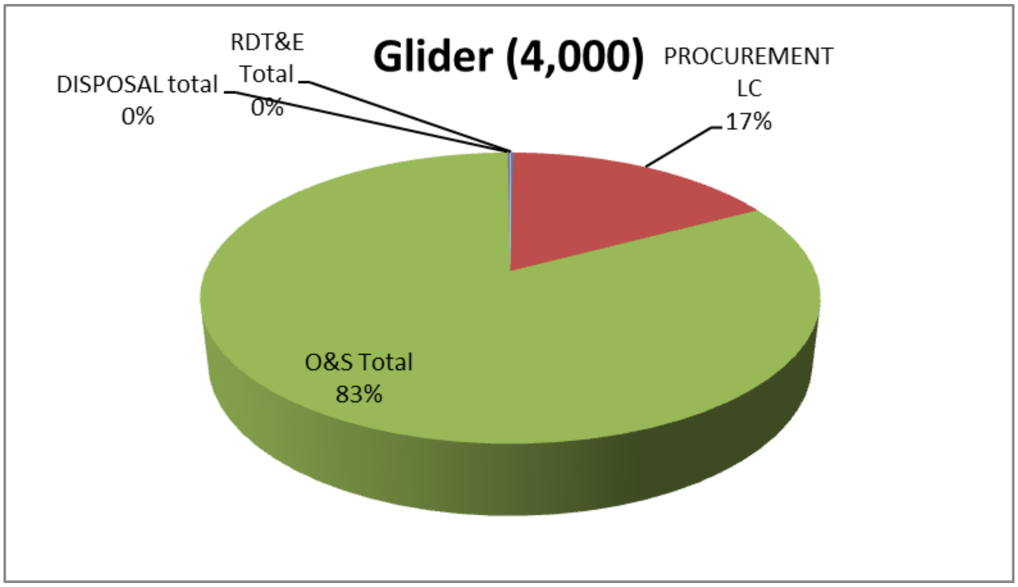

21" Recoverable Learning Curve
$3,300,000.00
$3,100,000.00
$2,900,000.00
$2,700,000.00
$2,500,000.00
$2,300,000.00
$2,100,000.00
$1,900,000.00
$1,700,000.00
$1,500,000.00
1
11
21
31
41
51
61
71
81
91
101
111
121
Units
21" Recoverable

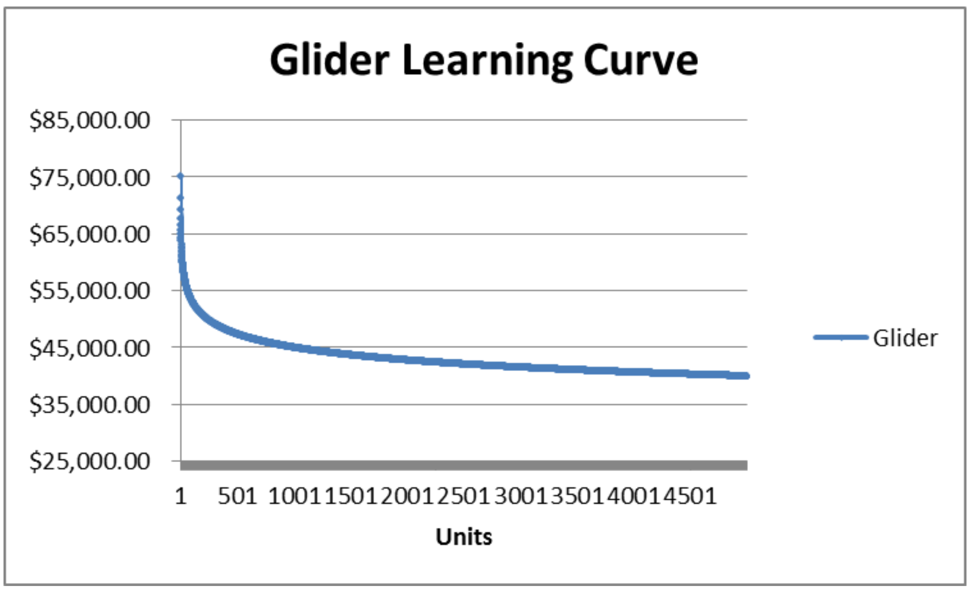


Glider Life Cycle Acquistion
3500
3000
2500
2000
1500
1000
500
0
Number of Vehicles
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Years
Glider
Loss Rate
Build Rate
Total Built



21" Expendable O&S Cost
Replacement 8%
Recovery 4%
Energy Cost 4%
Maintenance 34%
Software 50%


Glider (4,000)
RDT&E Total 0%
DISPOSAL total 0%
PROCUREMENT LC 17%
O&S Total 83%


Glider Learning Curve
$85,000.00
$75,000.00
$65,000.00
$55,000.00
$45,000.00
$35,000.00
$25,000.00
1
501
1001
1501
2001
2501
3001
3501
4001
4501
Units
Glider

APPENDIX H: MATLAB UUV DECEPTION MODELING CODE

```
% UUV Deception Operations
% Game Theory/Decision Tree Model of UUV employment against enemy naval
% exercise or operation

% develop payoff for blue and red and utility for blue.
% payoff and utility variables are three dimensional in:
% (engagement, fraction covert employment, red aggressiveness)
% calculated for 20 engagements, blue covert employment 0 to 1,
% and 5 levels of red aggressiveness


% prob detection/no detection_covert/overt
Pd_C = .2;
Pd_O = .95;
Pnd_C = 1 - Pd_C;
Pnd_O = 1 - Pd_O;

% Red mixed strategies of aggressiveness
% 1-con, 2-mod, 3-agg, 4-counter, 5-counter high
Pp = [.2 .3 .7 .3 .2]';
Pc = [.7 .5 .1 .2 .1]';
Po = [.1 .2 .2 .5 .7]';

% Engagements
eng = [0:19]';

% payoff_blue/red_covert/overt-no detect/prosecute/cease ops/observe
payoff_b_cn = 2-exp(-eng/2);
payoff_b_cp = exp(-eng);
payoff_b_cc = -ones(20,1);
payoff_b_co = -eng/10-2;

payoff_b_on = 3-exp(-eng/2);
payoff_b_op = 1.5*sin((eng+1.4)/4.5)+1.5;
payoff_b_oc = exp(-eng);
payoff_b_oo = -eng/10-1;

payoff_r_cn = exp(-eng)-1;
payoff_r_cp = eng/10+1;
payoff_r_cc = exp(-eng);
payoff_r_co = 2+eng/10;

payoff_r_on = exp(-eng)-3;
payoff_r_op = exp(-eng)-3;
payoff_r_oc = zeros(20,1);
payoff_r_oo = 1+eng/10;

% Blue mixed strategy for employment, covert and overt
strat_b_c = [0:.1:1]';
strat_b_o = 1-strat_b_c;
```

```
% Indices for 3-dimensional payoff or utility database
% i-engagement (1 through 20)
% j-blue mixed strategy (fraction covert - 0 to 1)
% k-aggressiveness (1 through 5)

for i=1:20
    for j=1:11
        for k=1:5
            pay_b(i,j,k) = ((Pp(k)*payoff_b_cp(i) +...
                Pc(k)*payoff_b_cc(i) + Po(k)*payoff_b_co(i))*Pd_C +...
                Pnd_C*payoff_b_cn(i))*strat_b_c(j) +...
                strat_b_o(j)*((Pp(k)*payoff_b_op(i) +...
                Pc(k)*payoff_b_oc(i) +...
                Po(k)*payoff_b_oo(i))*Pd_O + Pnd_O*payoff_b_on(i));

            pay_r(i,j,k) = ((Pp(k)*payoff_r_cp(i) +...
                Pc(k)*payoff_r_cc(i) + Po(k)*payoff_r_co(i))*Pd_C +...
                Pnd_C*payoff_r_cn(i))*strat_b_c(j) +...
                strat_b_o(j)*((Pp(k)*payoff_r_op(i) +...
                Pc(k)*payoff_r_oc(i) +...
                Po(k)*payoff_r_oo(i))*Pd_O + Pnd_O*payoff_r_on(i));
        end
    end
end


% exponential utility adjustment with constant risk tolerance
RT_b = 1;

% H_b is max blue payoff for that engagement, L_b is min payoff
for i=1:20
      H_b(i)  =  max([payoff_b_cn(i),  payoff_b_cp(i),  payoff_b_cc(i),
            payoff_b_co(i),        payoff_b_on(i),        payoff_b_op(i),
            payoff_b_oc(i),payoff_b_oo(i)]);
      L_b(i)  =  min([payoff_b_cn(i),  payoff_b_cp(i),  payoff_b_cc(i),
            payoff_b_co(i),        payoff_b_on(i),        payoff_b_op(i),
            payoff_b_oc(i), payoff_b_oo(i)]);
end

% u calculates utility of the payoff on scale from 0 to 1
u  =  @(H_b,  L_b,  RT_b,  payoff)  (1-exp(-(payoff  -  L_b)/RT_b))/(1-
exp((L_b-H_b)/RT_b));

for i=1:20
    for j=1:11
        for k=1:5
            util_b(i,j,k)                                              =
((Pp(k)*u(H_b(i),L_b(i),RT_b,payoff_b_cp(i)) +...
                Pc(k)*u(H_b(i),L_b(i),RT_b,payoff_b_cc(i)) + ...
                Po(k)*u(H_b(i),L_b(i),RT_b,payoff_b_co(i)))*Pd_C +...

Pnd_C*u(H_b(i),L_b(i),RT_b,payoff_b_cn(i)))*strat_b_c(j) +...

strat_b_o(j)*((Pp(k)*u(H_b(i),L_b(i),RT_b,payoff_b_op(i)) +
```

```
                Pc(k)*u(H_b(i),L_b(i),RT_b,payoff_b_oc(i)) +...
                Po(k)*u(H_b(i),L_b(i),RT_b,payoff_b_oo(i)))*Pd_O +...
                Pnd_O*u(H_b(i),L_b(i),RT_b,payoff_b_on(i)));
        end
    end
end

plot(strat_b_c, util_b(:,:,1))
grid
title('Blue Utility against Red Conservative')
xlabel('Fraction of Blue Employment Covert')
legend('Location','BestOutside')

figure(2)
plot(strat_b_c, util_b(:,:,2))
grid
title('Blue Utility against Red Moderate')
xlabel('Fraction of Blue Employment Covert')
legend('Location','BestOutside')

figure(3)
plot(strat_b_c, util_b(:,:,3))
grid
title('Blue Utility against Red Aggressive')
xlabel('Fraction of Blue Employment Covert')
legend('Location','BestOutside')

figure(4)
plot(strat_b_c, util_b(:,:,4))
grid
title('Blue Utility against Red Counter')
xlabel('Fraction of Blue Employment Covert')
legend('Location','BestOutside')

figure(5)
plot(strat_b_c, util_b(:,:,5))
grid
title('Blue Utility against Red Counter High')
xlabel('Fraction of Blue Employment Covert')
legend('Location','BestOutside')

figure(6)
plot(strat_b_c, pay_b(:,:,1))
grid
title('Blue Payoff against Red Conservative')
xlabel('Fraction of Blue Employment Covert')
legend('Location','BestOutside')

figure(7)
plot(strat_b_c, pay_b(:,:,2))
grid
title('Blue Payoff against Red Moderate')
xlabel('Fraction of Blue Employment Covert')
legend('Location','BestOutside')
```

```
figure(8)
plot(strat_b_c, pay_b(:,:,3))
grid
title('Blue Payoff against Red Aggressive')
xlabel('Fraction of Blue Employment Covert')
legend('Location','BestOutside')

figure(9)
plot(strat_b_c, pay_b(:,:,4))
grid
title('Blue Payoff against Red Counter')
xlabel('Fraction of Blue Employment Covert')
legend('Location','BestOutside')

figure(10)
plot(strat_b_c, pay_b(:,:,5))
grid
title('Blue Payoff against Red Counter High')
xlabel('Fraction of Blue Employment Covert')
legend('Location','BestOutside')
```

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